Investigating the Potential of a Virtual Reality Training Simulator for Aerial Firefighting and Air Attack Supervision

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Kia kaha, Kia maia, Kia manawanui!

Tehei mauri ora!

Abstract

This thesis investigates the design and implementation of a virtual training system for Air Attack Supervisors (AASs), an understudied, complex decision-making domain which plays a critical leadership role in large scale aerial wildfire firefighting. The AAS operates as a co-pilot from a helicopter known as the Air Operations Platform (AOP) and must be effective at directing helicopters and fixed-wing aircraft from a tactical aerial viewpoint.

While there are many talents which make a high quality AAS such as leadership, Crew Resource Management (CRM), emotional intelligence and self-awareness, the AAS relies on three core abilities: *situation awareness, effective communication* and their *decision making* ability in stressful environments. These core abilities are fundamental skills required for effective AAS and are the focus of this training simulator design. This thesis addresses the problem of the training deficit in high-stress, high-risk aviation-based wildfire firefighting.

A computer-based Virtual Reality Training System (VRTS) was designed following research and development principles focused on creating user goal-focused training, with immersive multi-sensory Virtual Reality (VR) to provide low-cost any-time situated training experiences for Naturalistic Decision Making (NDM) in aerial firefighting. This system enhances the state-of-the-art in simulation training as

this particular domain is unexplored academically, and current real-world training solutions are not only expensive, but are also dangerous, lack in cognitive challenges, and do not immerse trainees in a typical multi-actor aerial firefighting response situation. This limits the psychological stress and challenges normally experienced in a real-world wildfire.

The following key lessons are learned from this research: psychological fidelity is more important to an effective training system over physical fidelity. Situation Awareness (SA) is better acquired through immersive displays. Expert AAS users find a way to overcome communication problems to ensure their instructions are delivered. Heart-Rate Variability (HRV) measurements between real-world field and VRTS training exercises showed no significant difference between the training types suggesting similar stress levels are obtained in each condition.

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Acronyms

Air Attack (AA) The shorthand radio call for the Air Attack Supervisor.

Air Attack Supervisor (AAS) An experienced firefighter trained as a co-pilot who manages fixed-wing and helicopter activity operating from an AOP. The main target population for the research in this thesis.

Air Operations Platform (AOP) A helicopter which acts as a tactical observation platform for gaining SA and management of aviation assets over a fireground, the operating environment of the AAS.

Air Support Supervisor (ASS) A firefighter who manages aerial assets from the ground and ensures smooth operations.

Braided River Model (BRM) An indigenous methodology used to combine different streams of knowledge [88].

Coordinated Incident Management System (CIMS) New Zealand's established disaster response framework for emergency response.

Crew Resource Management (CRM) The effective use of all available resources, people, equipment, time, and information. By effectively using these resources to their fullest potential, crews behave more effectively, efficiently and in synergy [84].

Critical Incident Stress (CIS) Stress that is experienced during a critical incident such as a natural disaster, bodily harm or a near death experience [106].

Cylindrical Projection Display (CPD) A cylindrical projection-based display system, which uses projection mapping software to fit the projected image onto the screen to make it visually accurate.

Dundee Stress State Questionnaire (DSSQ) A standardised questionnaire used to measure subjective stress.

Electroencephalogram (EEG) A test that measures electrical activity in the brain using small, metal electrodes attached to the scalp [1].

Fire and Emergency New Zealand (FENZ) New Zealand's unified urban and rural firefighting emergency first responder organisation responsible for handling fire, emergency and disaster response. The primary collaborator to this research, with approximately 3000 career staff and 12000 volunteers.

Head Mounted Display (HMD) A display with a close proximity to the user's eyes to graphically provide computer generated visual stimulus.

Heart-Rate Variability (HRV) The change in heart rate which can indicate the state of stress that can be measured with ECG.

High Reliability Organisation (HRO) An organisation that follows strict operating procedures to prevent poor outcomes, improve safety and reduce mishandling situations.

Igroup Presence Questionnaire (IPQ) "A standardised questionnaire for measuring the sense of presence experienced in a virtual environment".

Naturalistic Decision Making (NDM) How experts make real-life decisions in dynamic conditions under time pressure, uncertainty and risk. Involves multiple individuals and experienced decision makers in high-stakes organisational settings [74].

Operations Manager (OM) A firefighter who coordinates the emergency response using ground and air division assets and must create and maintain shared situation awareness.

Post-Traumatic Stress Disorder (PTSD) "A mental health condition that's triggered by a terrifying event — either experiencing it or witnessing it. Symptoms may include flashbacks, nightmares and severe anxiety, as well as uncontrollable thoughts about the event." [3].

Push-to-Talk (PTT) A means of instantaneous communication used in radio communication to allow two-way conversations with a momentary button to change between voice transmission and reception transmitted from one to many.

Rural-Urban Interface (RUI) The locations where human civilization and the wild rural areas overlap, creating complex environments for wildfire emergency response involving humans.

Safety Effectiveness Efficiency & Logistics (SEEL) All aircraft operations must consider these factors for operation. Leadership teams can ensure these factors are being met by applying rigorous pre-planning risk management and analysis.

Short Stress State Questionnaire (SSSQ) A shorter version of the standardised DSSQ questionnaire used to measure subjective stress.

Simulation Based Training (SBT) Training which recreates complex, often high-risk situations that may be experienced in the real world. Often uses computer technology to enhance the simulation fidelity.

Simulator Sickness Questionnaire (SSQ) A questionnaire designed to subjectively measure simulator sickness.

Situation Awareness (SA) The ability to understand a given situation to a degree in its entirety. Multiple sources of information through vision and communication are used to build and maintain a mental model [49].

Situation Awareness Global Assessment Technique (SAGAT) A stop probe technique used in simulation for evaluating the situation awareness of a participant in regards to the virtual environment being experienced.

Subject Matter Expert (SME) An expert of a particular field or domain.

User-Centered Design (UCD) A process for designing complex interactive systems, designed with the user in mind.

Virtual Environment (VE) A computer generated interactive graphical environment.

Virtual Reality (VR) A technology that manipulates our senses into believing that something that is being experienced is real [82].

Virtual Reality Training System (VRTS) A training system with the objective of practising complex tasks in a safe environment.

Terminology

fidelity How close to reality a simulated environment is, which is often described in either physical or psychological aspects of realism.

helmet-fire A term used to describe the experience of being subjected to frequent and numerous channels of radio communication, through the multi-channel radio system embedded within the flight helmet.

macro-cognition A state of combined and shared knowledge between inter operable teams and organisations working together with a command and control or chain of command type environment [75].

presence The feeling of mental engagement within a virtual environment, experienced through the manipulation of the senses.

radio inject During training this type of radio stimulus is used to force trainees to use CRM, SA and decision making abilities.

recce Pronounced wreckee, it is a verbal report of the current situation otherwise known as a situation report (Sitrep).

sitrep A Situation Report of the given incident, also called a recce as a distinguished radio call.

Chapter 1

Introduction

This dissertation explores the design, implementation and evaluation of an immersive Virtual Reality Training System (VRTS) aimed at training for aviation-based firefighter disaster response in a complex, stressful decision making environment. This particular expert domain is known as Air Attack Supervision (AAS) or simply Air Attack (AA) in radio shorthand. This research investigates and draws upon different interdisciplinary *streams of knowledge* in a complex environment to create novel research outcomes. To conceptualise this process, the Braided River Model (BRM) [88] is used as an underlying strategy, which is an indigenous methodology to bind together interdisciplinary knowledge for pedagogy in education.

Braided rivers are a natural phenomenon (see Figure 1.1) made up of numerous and dynamic river braids or *streams of knowledge* that flow in synergy, become flooded and naturally change path around obstacles. The dynamic nature of the streams imply how the strengths of interdisciplinary knowledge can combine and flow harmoniously to navigate through unexplored domain or territory.

Figure 1.1: The Rakaia Braided River, Te Waipounamu, Aotearoa (New Zealand) Photo Credit: Robin Hartley

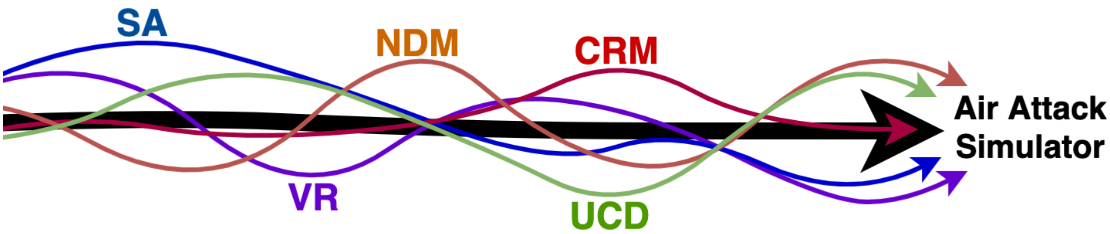

Figure 1.2: The braided river model used to combine complex interdisciplinary knowledge to develop the Air Attack Virtual Reality Training Simulator

In the case of a VRTS designed for aerial firefighting, four major braids of knowledge are combined from the following interdisciplinary domains: *Naturalistic Decision Making* (NDM), *Situation Awareness* (SA), *Crew Resource Management* (CRM) and *Virtual Reality (VR)*. These domains are then investigated with *User-Centered Design (UCD)* processes as a fifth braid, shown in Figure 1.2, which constrains this research to these streams of knowledge.

This process may be replicated as a method for developing other user task-focused VRTSs in wider applications involved in high-risk complex domains such as disaster response, police enforcement or for military application.

This originality of this research is highly significant as very few published research articles exist in the specific domain of aerial firefighting. Many other high-stress and high-risk occupations such as aviation, military, disaster and emergency response domains can benefit from the insights within this research on simulation that focuses on decision making in complex environments.

1.1 General Overview

This PhD research addresses the training issues faced by aerial firefighters specifically for AASs and how to improve training outcomes by designing an occupationally specific VRTS following UCD processes. It is critical for a successful outcome to have a clear understanding of the target end user and their objectives in mind. The objectives here are to investigate how VR can provide an effective training environment for high-risk, high-stress occupations. High-level cognitive skills such as SA, communication and decision making can be practised safely and effectively within a VRTS, increasing team confidence, performance and leadership capabilities [133].

Research has shown that high fidelity simulations can be beneficial for complex domains if designed and built correctly around end user demands, goals and objectives [133]. Being both high-cost and high-risk in nature, AA is a particularly stressful decision making environment. We explore if the occupationally relevant stressors of both physical and psychological *fidelity*, can be reproduced realistically in the virtual world. These physical and psychological stressors are used to enhance the level of training *presence* to enable a situationally relevant VRTS. The end result is the creation of more frequent training opportunities for AAS, improving responder confidence and efficiency.

Following a user-focused design and research strategy to the problem, we designed and evaluated an AAS VRTS against the needs of the end users. This resulted in the design improvements made to the VRTS following an iterative design process with feedback from our target end user. By following this methodology, we ensured that the work is ecologically valid and that the overall training goals and objectives from the VRTS were achieved.

This research explores the unique domain of VR being used as a training application for AAS in aerial firefighting. The research adds original and significant research to Simulation Based Training (SBT) for decision making in complex environments. While AA is the target domain and is unique, this research has a wider appeal to other complex NDM domains such as aviation, military, search and rescue, police and other disaster response.

1.2 Original and Significant Contributions

The main contributions of this thesis are as follows:

- A user-focused investigation for AAS, with SME interviews, a focus group study and in-the-wild observational studies, which provided the context of the user and the occupational conditions that they are subjected to, helping to uncover the fundamental aspects of the occupation.

- The design and implementation of a multi-sensory collaborative VRTS that can be used by AAS trainees for practising tasks and other occupationally relevant skills in a NDM environment.

- An ecologically valid set of experimentation and results that ensure the findings are tangible to AAS, as well as other complex high-stress, NDM environments.

1.3 Research Publications

In addition to the contributions of this thesis, the following four peer-reviewed publications have resulted directly from this dissertation. These articles contribute to the research fields of VR, SBT and NDM in a complex environment.

- *R. M. S. Clifford, H. Khan, S. Hoermann, M. Billinghurst & R. W. Lindeman, "Development of a Multi-Sensory Virtual Reality Training Simulator for Airborne Firefighters Supervising Aerial Wildfire Suppression," 2018 IEEE Workshop on Augmented and Virtual Realities for Good (VAR4Good), Reutlingen, 2018, pp. 1-5.* [38]

- *R. M. S. Clifford, S. Hoermann, N. Marcadet, H. Oliver, M. Billinghurst & R. W. Lindeman, "Evaluating the Effects of Realistic Communication Disruptions in VR Training for Aerial Firefighting," 2018 10th International Conference on Virtual Worlds and Games for Serious Applications (VS-Games), Wurzburg, 2018, pp. 1-8.* [40]

- *R. M. S. Clifford, S. Jung, S. Hoermann, M. Billinqhurst & R. W. Lindeman, (2019, March). "Creating a Stressful Decision Making Environment for Aerial Firefighter Training in Virtual Reality," In 2019 IEEE Conference on Virtual Reality and 3D User Interfaces (IEEEVR) (pp. 181-189). IEEE.* [37]

- *R. M. S. Clifford, H. Engelbrecht, S. Jung, H. Oliver, M. Billinghurst, R. W. Lindeman & S. Hoermann (2020, March) "Aerial firefighter radio communication performance in a virtual training system: radio communication disruptions simulated in VR for Air Attack Supervision," The Visual Computer, 2020, 1-14.* [39]

1.4 Problem Statement

There is a limited amount of training or opportunities to maintain currency for AAS firefighters prior to the fire season. Existing training is effective but could be supplemented with technology. The main problem this PhD research addresses is the training deficit in aerial firefighting. The goal is to improve AAS confidence by providing safe, task-focused and more frequent practise opportunities.

More frequent and extreme weather behavior as well as increasing temperatures around the globe [56; 59; 123] threaten our existence, with multi-million dollar financial burden each year [7]. Fire seasons increase by approximately 20 days each year causing an overlap between northern and southern hemispheres [56; 109]. Flannigan et al. suggest that conventional and current day fire management strategies will no longer be effective in the future [56]. These disasters take lives [54], cause severe ecological damage [138], loss of wildlife habitat and biodiversity [16; 53; 117]. The areas in which urban housing and rural areas co-exist, known as the Rural-Urban Interface (RUI) [10], are expanding, further encroaching on one another which puts houses and people's livelihoods at risk (see Figure 1.3) [10; 121], resulting in significant financial impact and economic damage [85; 121]. This problem exists all around the world, causing widespread devastation, particularly in places such as Australia, America, Canada and New Zealand [109].

Current forest management policies prevent the natural processes for forests to manage their own density [30]. The unfortunate effect of this is that forests and grasses are more dense and significantly more volatile due to the increase in biomass [30; 115] as the litter from trees is compounded. Forest fires inevitably become more destructive due to the combination of the large volatile biomass, strong winds and hot weather conditions, creating dangerous fire weather situa-

Figure 1.3: The 2017 Port Hills fire [44], captured from the University of Canterbury by the Author, indicating the proximity of human society with the RUI.

tions [109]. Additionally, yearly increase in climate temperature greatly increases the likelihood of severe fire risks and the disastrous effects that follow [15].

Wildfires and forest fires cause severe environmental destruction affecting wildlife as well as human life, and contribute to climate change by releasing heavily concentrated carbon in the form of smoke into the atmosphere [15]. Climate change effects cause more frequent and ever increasingly dangerous civil disasters each year [121; 123]. Emergency services need to be better prepared for fire seasons in particular where wildfires are most catastrophic [121].

In order to combat large scale wildfires, fixed-wing aircraft and helicopters are deployed to support ground crews [111]. Aviation vehicles such as helicopters and fixed wing aircraft are retrofitted to carry water or fire suppressant [135], or are built specifically for the purpose of fighting wildfire [139]. Although aircraft are a highly effective tool for firefighting [28], their usage carries a substantially high degree of risk and occupational stress that is known to have an adverse effect on decision making [131]. Without sufficient training, occupational stress can develop and may contribute to Critical Incident Stress (CIS) [106].

1.4.1 Motivation

Existing literature and feedback from SME suggests that training simulators of any fidelity being used in complex high-risk environments must ensure that the psychological or cognitive aspects of the training are the main focus, instead of primarily increasing the immersive physical elements [133]. To ensure that the results of the system support the main aspects of the training, the system must be designed to support the development of cognitive skills, using the least amount of physically immersive elements necessary to reach a high-level of engagement or presence within the situation [133].

AA must follow strict operational procedures in a multilateral organisational command structure. Aerial firefighting in New Zealand relies heavily on private helicopter and fixed-wing aircraft contractors to support firefighter crews on the ground. Contracted pilots are a subset of the air operations division, and are treated as equals to firefighters on the fireground. While combating wildfires, intelligence officers, operations management, ground crews and aircrews must all cooperate effectively and efficiently with one another to execute multi-lateral firefighting strategies under the Coordinated Incident Management System (CIMS) [103]. They must develop a macro-cognition [81] with shared SA, to avoid making bad decisions through lack of current or quality information, poor communication or complacency. They must operate highly effectively as a team, by utilizing CRM [84]. Wildfire firefighters are subjected to long durations of occupational stress as well as CIS [106]. These conditions are both physically and mentally demanding, when an extended duration leads to ongoing stress and fatigue [106].

A certain level of expertise is required in both, the aviation and the firefighting domains, to perform decision making tasks and conduct aerial operations effectively with confidence in a fast-moving dynamic environment. To achieve this, both firefighters and commercial aviation companies must regularly practise with one another, using in-the-field experiences and situated classroom exercises to develop expertise, maintain their level of skill or skill currency and be confident in their ability to respond quickly and efficiently. However, the current field training methods are very expensive to conduct, difficult to organise, infrequent and do not accurately recreate the conditions of a real wildfire event. This creates a desire to augment existing training with technology.

In comparison to their urban counterparts, rural wildfire firefighters are widely dispersed over large bodies of wild, rough terrain and in remote locations, which makes it difficult to organise large scale team training exercises. Financial costs for running aircraft in field training exercises as well as logistics issues also make it challenging to conduct frequent field training opportunities and is usually limited to a small number of aircraft. During a real wildfire event, the number of aircraft in use is significantly larger along with operating costs. Having a larger number of people to communicate with at any given time can be very confusing and hard to maintain, which creates an effect known within the industry as helmet-fire. To simulate this, radio-only exercises are conducted in training sessions to practise radio communications, but without the use of aircraft. Although effective at creating psychologically challenging stimuli, this type of training lacks the atmosphere of a real situation or the context of fighting a real fire, relying on trainees to use their imagination.

Investigation into how to create better training outcomes suggests the use of Simulation Based Training (SBT), VR and other multi-sensory immersive technologies [42] as an effective supplement to field training, however care must be taken to ensure end user goals are being reached [133]. Herein lies the motivation to design and build a mentally and physically challenging training system that enables firefighters and pilots training for any situation, and providing currency training with the necessary skill set for the occupation such as SA, communication and decision making.

1.4.2 Research Questions

Considering the above, the following questions about the use of VRTS for AAS need to be answered:

Q_1: *What fundamental aspects of AAS must be captured to ensure the VRTS is focused on the AAS training goals?*

Q_2: *What mental and physical conditions of the AAS occupation are required in the simulator to provide an immersive training experience?*

Q_3: *What display technology is more appropriate for AAS VR training based off user requirements?*

Q_4: *What communications challenges create a stressful AA environment?*

Q_5: *How do expert AASs react to stressful conditions?*

Q_6: *Can a VRTS create similar stress levels as a real training exercise for AAS?*

1.5 User-Centered Design

In this section, we briefly explain the approach of UCD shown in Figure 1.4 that was used to create a VRTS for AAS in the context of this thesis. UCD according to the Interaction Design Foundation, is an "iterative design process in which designers focus on the users and their needs in each phase of the design process.

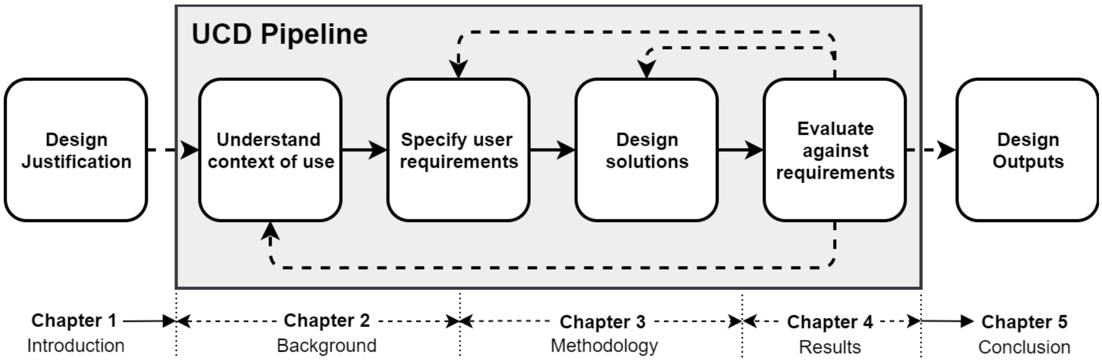

Figure 1.4: The User-Centered Design development model, adapted from Interaction Design Foundation [13], with thesis chapters added addressing each stage

In UCD, design teams involve users throughout the design process via a variety of research and design techniques, to create highly usable and accessible products for them." [13].

This methodology was used for the research investigation and the implementation of the prototype VRTS and is fundamental to this research, due to the focus and involvement it has on the user goals and needs [13; 51]. UCD is an ISO standard for developing interactive systems focusing on human ergonomics (ISO 9241-210:2019) [68]. Following the UCD process, to *understand the context of use*, background information is presented in Chapter 2. Next, to *specify the user requirements*, detailed information is provided in Chapter 3, Section 3.1 in the form of interviews, observational studies and a focus group. Following this, prototype *design solutions* are presented in Chapter 3, Section 3.4. The prototype, designed in an iterative cycle, is *evaluated against requirements* found using scientific methodology in Chapter 4. After three iterations, we reach the final design output and conclusion of the thesis presented in Chapter 5.

UCD was used to optimize the User eXperience (UX) or the usability of an interactive system. This is to ensure the training objectives were being adequately catered for, based on understanding the context of use and by specifying user requirements. This enabled costly design errors to be avoided at each stage of development or system iteration. The system was evaluated using validated questionnaires and physiological measures during actual firefighter training for AA, aiming to answer the research questions presented in Section 1.4.2. With this approach we kept the goals of the trainers in mind as well as how the trainees were experiencing the system using scientific methodology to avoid researcher or user bias.

1.5.1 User Research

To understand the context of use and to specify the user requirements, we conducted a multi-faceted user research investigation, conducting interviews with SMEs, AAS focus groups and in-situ observational studies with novice and expert trainees. This helped to create an understanding of the end user, the context and the objectives of AAS trainers. This led to an optimized, user goal focused training system, avoiding implementation of redundant or unnecessary features. We evaluated the usability of the system with a range of users, from novices to highly experienced professional firefighters to discover how different end users experienced the system, how the system benefited the user in terms of expertise and level of simulation fidelity, to explore the issues around these aspects [133]. For any occupational UX, we need to understand the requirements of the job and what the user expects out of the training system. Data can be collected by being immersed within the user domain as close as possible to experiencing it in the wild, to fully understand the emotions and stresses experienced by the operator. In lieu of experiencing a real air attack wildfire response, it can also be achieved by attending training sessions in a non-invasive manner to gain a better understanding of the tasks, skill requirements and operating conditions.

UX research strategies and methodology are aligned to scientific methods using qualitative information that is obtained through open-ended questions and interviews, quantitative statistical analysis using validated questionnaires, physiological data and performance evaluation. This data is used to fuel our design iterations and also used to test our hypothesis and answer the research questions, presented in Section 1.4.2.

1.5.2 Iterative Design Process

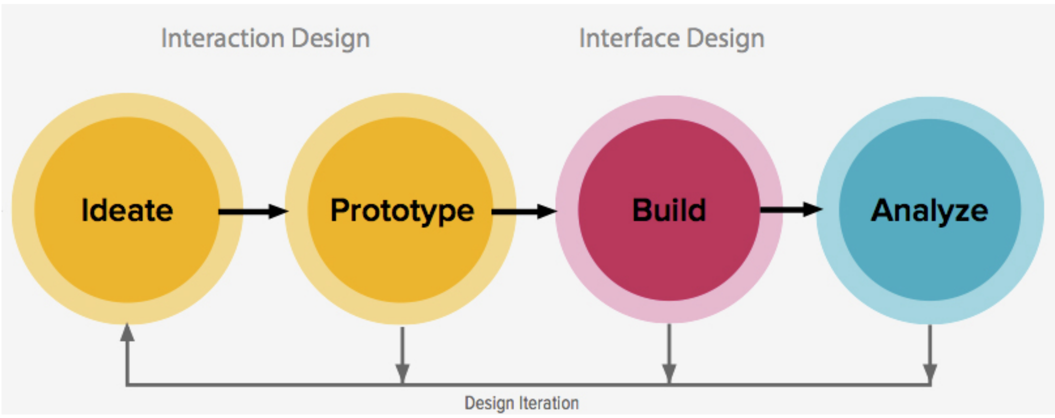

Figure 1.5: The iterative design process, image from ZURB [150]

In our system development process, we started the design by engaging with Fire and Emergency NZ SME, trainers and officers to ensure that what we provided was tailored to their needs from the system being developed with the user research. On each design iteration, empirical studies were conducted to evaluate the system with a range of users from novice to experienced firefighter personnel, creating role play scenarios to simulate typical usage and ensure that the system met their requirements. To guide the future design of the VRTS we evaluated the usability of the system with the feedback and observed experiences of the end user at stages of development or iterations following the iterative design process shown in Figure 1.5. Engaging with the end users throughout the development process allowed us to focus on their needs, making design changes based on their feedback and observations in prototype testing [14]. This avoided investing time, energy and resources into features that provided little benefit to the training.

1.6 Thesis Structure

This section discusses the remaining content of the dissertation chapters. In ***Chapter 1***, the overarching research strategy of the BRM was provided with a problem statement and motivation for this research, followed by the research questions and the scientific contributions of this research. At the end of ***Chapter 1***, the UCD process used for the VRTS is briefly described. ***Chapter 2*** provides an in-depth literature review of fundamental aspects for this research such as NDM or handling decision making under stress, SA, communication CRM, VR and SBT as well as essential background knowledge regarding AA aviation firefighting. ***Chapter 3*** provides an end user research investigation, then specifies the software and hardware components for the VR training simulator, measurements used for evaluation and the iterated prototype. ***Chapter 4*** describes the empirical studies performed to answer our research questions, the results from experimentation, followed by discussions about the results on each experiment. ***Chapter 5*** provides conclusions about the research and outlines future work remaining for investigation.

Chapter 2

Background

This chapter provides background information for understanding the subject matter of this research. This includes outlining the research domain (combining principles of aviation, firefighting and military strategy), followed by concepts regarding VR, training, and simulation.

Firefighters and emergency responders are the first line of defense when a disaster occurs. In New Zealand, Fire and Emergency New Zealand (FENZ) were the most trusted public sector organization in 2019, according to Colmar Brunton [58]. FENZ is a High Reliability Organisation (HRO), in which they must promote a work-safe environment and must be risk-aware, operating with the utmost care, efficiency, with minimal loss to themselves and to the public.

Although relied upon in life or death situations, firefighters face public scrutiny and can be prosecuted for subjectively poor performance or bad decision making [19]. For this reason, decisions and actions must be entered into a logbook in case of a legal dispute [5; 8]. FENZ personnel must conduct their operations carefully, following the Safety Effectiveness Efficiency & Logistics (SEEL) strategy as well as L.A.C.E.S. (see Figure 2.1) which must be used in any wildfire incident.

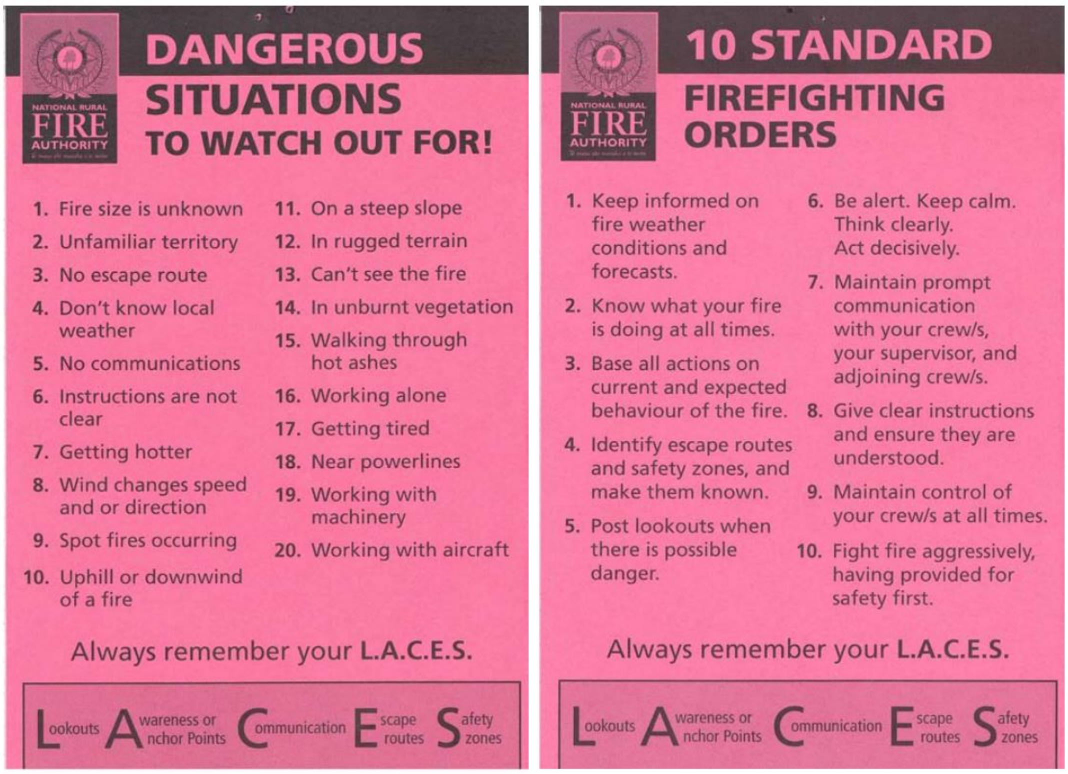

Figure 2.1: Lookouts, Awareness, Communication, Escape routes & Safety zones. The Wildfire Firefighting orders from Fire and Emergency New Zealand

The following section describes the Air Attack aerial firefighting domain including the human and machine assets required to keep air operations running smoothly.

2.1 Air Attack - Aerial Firefighting

Aerial firefighting uses helicopter and fixed-wing aircraft (see Figure 2.2) to aerially suppress wildfires using military-like planning, strategy and tactics [8] as an initial response and to support ground crews. Although aerial firefighting effectiveness has been questioned [111], it is considered one of the more effective methods to get water and fire suppressant to remote areas that are difficult to

Figure 2.2: Typical aircraft used in aerial firefighting: A helicopter fitted with a belly tank and snorkel (left) and a fixed-wing aircraft (right). An Air Attack training exercise in Rangiora, Te Waiponamu. Photo credit: Veronica Clifford

access. It is also effective to assist in the initial response to a reported fire and has a positive psychological effect on ground crew and civilians [28]. The main task for AA is to support the firefighter crews on the fire ground to divert wildfire from approaching housing and other assets [111].

In this section we discuss essential roles involved in aerial firefighting which keeps it operational. Table 2.1 is a non-exhaustive list of the roles in aerial firefighting, which shows the variety and complex nature of utilizing aircraft at wildfires. Many relationships between these people must be maintained in order to conduct effective aerial firefighting and support the overall firefighting operations.

Air attack requires many expert people on the ground and in the air to support the aerial operation with mental and physical engagement to make it operationally effective. These expert operators are in constant communication via radio and face-to-face, providing each other SA and working in concert with ground crew firefighters to help control wildfires from the air. It is a risky operation that takes place in remote wilderness areas with dense fuels and wild animal habitats [117].

Leadership, SA, communication and decision making in stressful situations are fundamental to the success of aerial firefighting, much like it is in military

Table 2.1: List of roles relating to aerial firefighting

Agency	Emergency occupation
In Air Operations	fire suppression, hover exit operations, para-firefighter/smoke-jumper, helicopter rappel operations, aerial drip torch operations, aerial incendiary operations.
Aerial Intelligence	UAV operator, air observers, aerial intelligence gathering, infrared hotspot mapping, live streaming, line scanning etc.
Ground Support	Air base managers, logistics and record keepers, Air Support Supervisor (ASS), retardant mixing crews, refilling teams
Agency and Incident Management	Senior agency Operations Management (OM), Incident controllers (IC), operations function leaders in Incident Management Teams (IMT), fire ground managers, air division commander, air operations managers, aircraft officers, state air desk operators.

operations [36]. In order to ensure these skills are maintained, frequent team training and practise is required to ensure people are confident and up-to-date with the best practises.

2.1.1 Aircrew

The Aircrew consists of helicopter and fixed-wing aircraft pilots, operating their respective aircraft to attack the fire. The AAS observes and manages the aircrew over the fire ground from a helicopter known as the AOP via radio communication (Figure 2.3).

2.1.1.1 Air Attack Supervisor

AAS are deployed when the scale of the aviation crew becomes unmanageable from the ground, or when the wildfire is showing signs of increased activity. Normally, when three or more aircraft are operational, this justifies the deployment of

Figure 2.3: The AOP cockpit, AAS on the left and helicopter pilot on the right.

an AAS. The AAS becomes a valuable team leader, enabling the aircrew carrying water to work in concert, and provides a tactical bird's-eye view of the situation. They provide an essential link in the chain of command under the Operations Manager (OM). The AAS operates as a co-pilot in the AOP and does not fly the aircraft. The AAS must focus on gaining SA and co-ordinating the aircrew, providing feedback on their performance and to provide orders from the Air Division Commander, OM or IC. FENZ follows the Command Incident Management System (CIMS) [105] command and control model, a distributed command management model that utilizes many leaders in a multi-lateral chain-of-command in order to conduct a large scale operation. AAS is a leadership role within this chain of command, managing the aerial resources, acting as an information node for SA. Trust and knowledge must be quickly built with the aircrew and with the AAS as their leader. High quality communication is the foundation to achieving this.

Table 2.2: List of commercial aviation roles

Aircraft Type	Commercial occupation
Fixed-wing	Aerial Search and Rescue (ASAR), agricultural spraying/top dressing, cargo/freight transport, passenger transport, charter/private transport, research.
Helicopter / Rotary-wing	Aerial sluicing, ASAR, aerial wire and cable stringing, remote access, power line inspection and survey, Lifting and crane services for construction and industry, police pursuit, transfer services, private/corporate and VIP charters, agricultural services, aerial photography and filming, advertising banner towing [12].
Drone / UAV	Hotspot mapping, aerial reconnaissance, ASAR, remote medical delivery, photography, power line inspection, building inspection, wildlife monitoring, security, environmental monitoring and conversation, land & forestry surveying.

2.1.1.2 Aircraft Pilots

Commercial aircraft pilots are currently the most commonly used pilots in New Zealand, and have their own ground crew, engineers and maintenance teams to support them in order to keep the aircraft operational. These are most typically helicopter and small aircraft companies performing numerous commercial operations [12; 43] see Table 2.2. Other jurisdictions and larger countries like America and Canada have a national response fleet and have established protocols for aerial firefighting [8].

Helicopters can carry anywhere from approximately 270L to 9500L of water or retardant, using either a belly tank or an under-slung bucket attached to a long line or short cable [135]. Helicopters are used for precision drops. Fixed-winged aircraft, predominantly used for transport, are converted to carry water. Light fixed-wing aircraft such as the Air Tractor can carry approximately 3000L [139]. Larger countries like Australia, America and Canada have dedicated national aerial firefighter fleets which utilize Large Air Tanker (LAT) or the VLAT Super-

Tanker which can carry approximately 15,000L to 70,000L respectively [9; 118]. Fixed-wing aircraft are especially effective at delivering fire suppressant ahead of a fire to stop its progress. Helicopters, while carrying less, provide greater precision and can get closer to the fireline where ground crews are operating.

In some cases, military aircraft may also be deployed [55]. Many military style aircraft are also converted for firefighter operations because of their carrying capacity and maneuverability [55]. Drone pilots are also used in some instances, but are restricted in their operation for safety. Currently, drones are not used for suppression but are very useful instead for intelligence gathering such as inspection and monitoring purposes [99; 140], detecting underground fires or hot-spot mapping [32]. Future use of drones is expected to increase for emergency and disaster response [32; 113; 136; 149].

2.1.2 Ground Crew

The support teams for the aerial assets work to keep the aircraft supplied with fuel and water ready on demand. The ground crew can be made up of firefighter personnel or the engineers and members of the contract company to keep the aircraft supplied and operational.

2.1.2.1 Air Support Supervisor

In a basic aerial operation consisting of one to two aircraft, it is usually not necessary to deploy an AAS and tasks can be managed from the ground. The operation still requires management of ground crews to provide water and fuel refill locations, strategy planning and to ensure the operation continues smoothly. In this situation, Air Support Supervisor (ASS) are prescribed to manage logistics and interactions with the OM and the aircrew. If the scale of the wildfire develops and requires a greater aerial response, it is often the ASS who then becomes AAS as the most experienced and likely to have the best current understanding of the situation or has the greatest SA on-site. The ASS in this situation is replaced with the next experienced officer. AAS and ASS are often trained similarly and are exposed to similar training exercises.

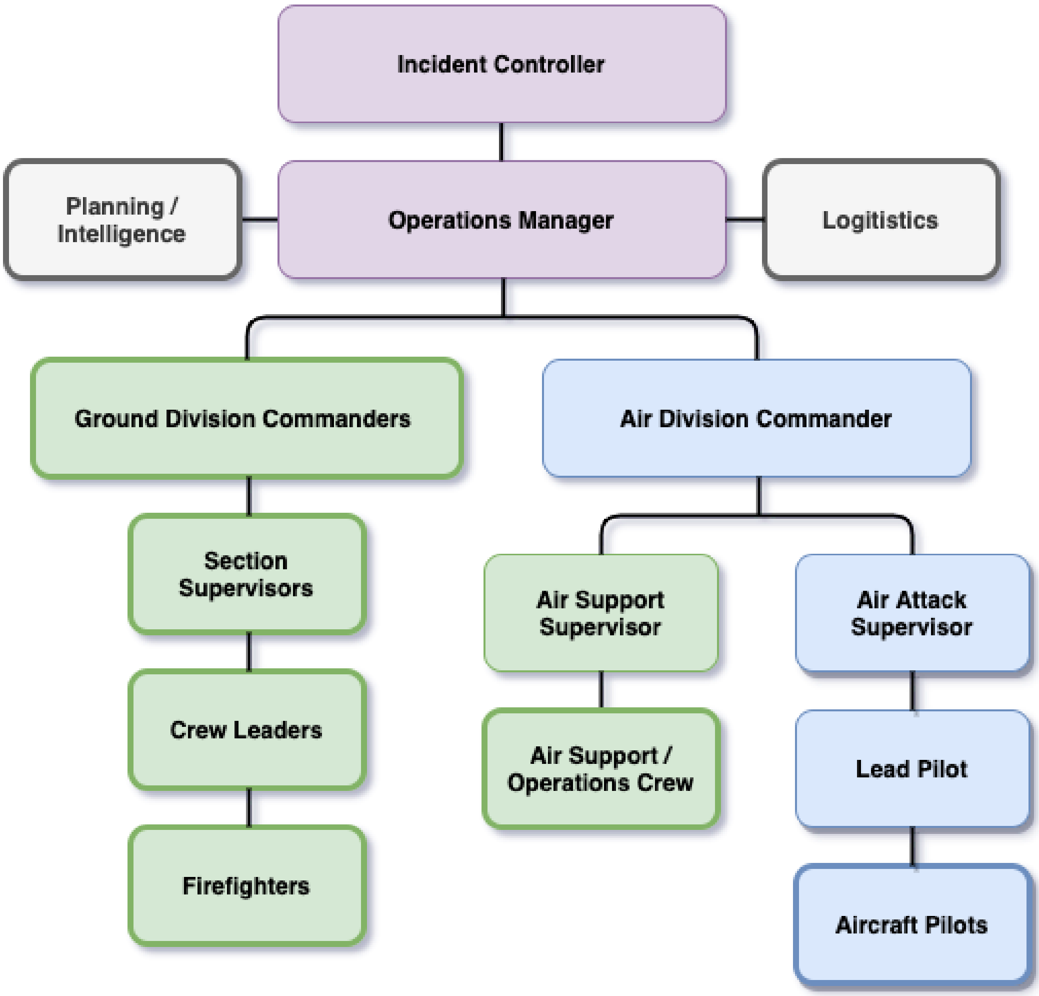

Figure 2.4: The command structure for a large wildfire. A thick border indicates more than one person potentially in the role. The Operations Manager often communicates directly with ASS and AAS for faster, up to date SA

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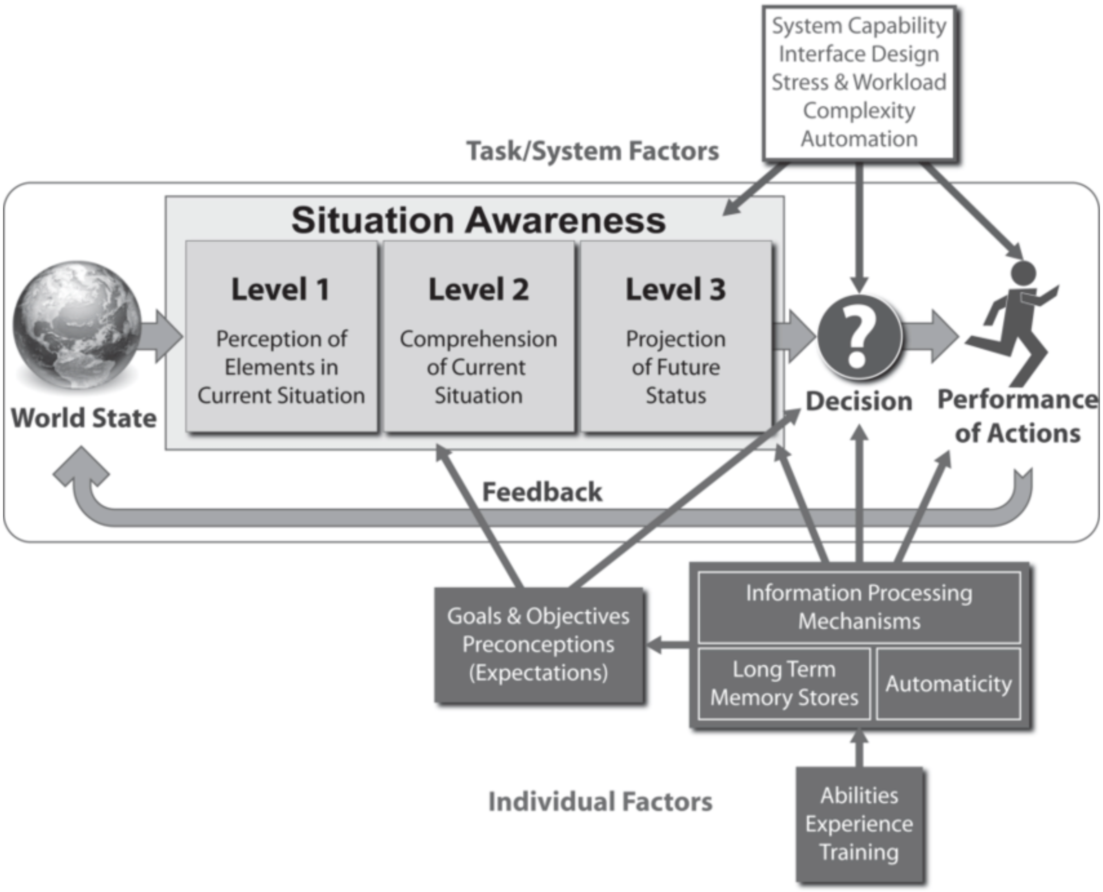

Figure 2.5: Endsley's model of SA and Dynamic Decision Making [50]

2.2 Situation Awareness

SA initially began in aviation psychology and then became a part of other safety critical systems [52]. Endsley et al. [51] define SA in terms of three levels: the perception of the elements (level one), comprehension of the situation (level two) and projection of future status (level three). According to Endsley, these three components make up the total SA someone can achieve [51]. Figure 2.5 provides the model proposed by Endsley [50; 51] exhibiting the relationship between SA and decision making in a dynamic or naturalistic situation.

It is critical in aviation to share SA understanding and undertake cooperative problem solving [101] building up macro-cognition. Accurate shared information is critical for effective high risk team operations [51; 92]. In the case of aerial firefighting, SA is experienced through several modalities: radio communication from aircrew, ground crew and from operations, as well as through the visually acquired information observed from an elevated viewpoint over the fire ground. Meanwhile, strategic planning and team briefings are used to share SA prior to conducting operations give advanced warning of fire location and hazards [49]. This is necessary to continue to operate with a safe and manageable risk [11]. This information together gives the total SA or a complete up-to-date understanding of the situation [51]. In terms of building and maintaining SA, the operator state is important to consider. Experiencing stress or anxiety impairs the higher cognitive ability required to build a mental model, communicate, and have comprehension and to predict how the situation will evolve. This can put lives at risk, which is why management of stress is important and being able to identify operator state vital [101].

An example of a hazard element from aerial firefighting and other low flying aircraft operations are wire-strike type hazards [2; 102]. Power lines and transmission towers with suspended reinforced cables can quickly force a helicopter to the ground, due to how difficult they are to see in the air [78; 102]. Technology may be used to detect these hazards but should not be solely relied upon but rather a multi-layered prevention strategy including hazard awareness training [78]. Prior knowledge of the hazard location is important to aerial response plans and as such must be built into the strategic knowledge and communicated with aircrew and ground crews [102]. Having this prior knowledge of the wires and hazards allows pilots to build SA and avoid incidents.

2.3 Communications

Across the different sectors using radio communication, it is found that communication errors are a major contributing factor to problem situations [124; 142]. In the aviation industry the majority of problems experienced are caused by communication failures, either human or mechanical, with between 60 to 80% from human error [142]. Interpersonal communication problems such as communication behavior or misunderstanding radio protocol was one of the major causes of deterioration in a crisis situation [142]. Poor communication is contagious and can effect everyone involved from flight crew to pilots and mechanics [142]. Viera et al. suggest the best way to bring a crisis situation under control is to restore communication to a high standard [142]. They suggest integrated Communication Based Training (CBT) should be built into the curriculum and maintained regularly. Unreported incidents, or not looking out for one another can easily lead to bad situations [141].

Miscommunication in aviation is one of the major issues regarding safety [100]. Factors such as poor audio quality, thick foreign accents, limited proficiency in the English language, as well as failure to use standardized radio protocol, all contribute to communication errors in aviation [142]. Having too much workload, hesitation or requirement to manage multiple items in one radio transmission severely degraded radio performance [100]. There are various layers of communication beginning at the planning stages through to real time fire ground communication and post-incident debriefing. Adequate leadership ensures that all members are communicating efficiently. Leadership is an important aspect for CRM as it enables teams to become highly functional [84].

A study was performed by Bosse et al. [23] to investigate how police officers practising interpersonal communication skills in a low-fidelity virtual simulator, consisting of an Artificial Intelligence (AI) driven 3D avatar or Embodied Conversational Agent (ECA), experienced through a computer monitor, can benefit police officers in handling or de-escalating a situation. In this study, trainees reported that they needed to establish an emotional connection with the other party which would often not come across in fixed spoken responses. Users also responded with a desire to increase the simulation fidelity by the use of a HMD to create a more personal or emotional connection with the avatars, as a computer monitor only affords the most basic of user immersion [23]. Saus et al. [120] performed a study on SA in a simulator for police firearms training. They found that the SA trained group showed a better cognitive ability and gave a lesser stress response to live fire situations as measured by Heart Rate Variability (HRV). They concluded that providing specific SA training in a live fire simulator where trainees must identify and shoot gunmen, but not civilians, improves the trainee's SA in such critical situations [120]. Coordinated or Network-centric warfare is a command and control doctrine which aims to provide greater communication ability, interoperability and information flow between coalition forces and their decision makers [104]. Provided that the information is reliable, current and accurate, high frequency SA can be achieved. Communication flow between agencies with a diverse range of personnel and vehicles using different technologies can be coordinated simultaneously, to quickly take the advantage, rapidly advancing to overcome the enemy. Gaining the advantage through superior technology is a core strategy for military operations, however an over-reliance on the technology can achieve the opposite effect, especially when tools are poorly used, through complacency or lack of training.

2.3.1 Crew Resource Management

CRM is a highly valuable set of skills for teams and organisations and when utilized effectively, acts as a force multiplier [84] and is fundamental to high quality communications. This effect emphasizes how highly skilled individuals working together in synergy are more effective than individuals working independently [84]. For inter-organisational effectiveness, all organisations must function similarly to each other, where individuals enter a state known as macro-cognition [75; 81]. Macro-cognition consists of several high-level cognitive processes found in collaborative team-based activities [75].

As defence or civil emergency response teams are run by many people using different machines or technologies, a high level understanding and the ability to utilize these resources is required to effectively coordinate the various teams and assets to solve the problems being addressed [75]. CRM has found its way into many High Reliability Organisations (HROs) as a method to reduce errors and improve performance within team environments such as: aviation [66], military [36; 71], maritime [71; 143], medical [48; 71] and firefighting [84].

CRM has many different aspects which contribute to its effectiveness such as leadership, task management and mission planning. Lubnau et al. [84] suggest that the critical elements pertaining to the firefighting industry are SA, leadership, fellowship, decision making and communication. Kanki et al. suggest that in addition to SA, decision making and communication, CRM also comprises of task management, stress management and fatigue management [71]. CRM is an effective way to utilize all available resources, minimizing risks and increasing overall performance. Military, aviation [66] and firefighting [84] amongst other emergency domains practise CRM and operate as a HRO. This greatly enhances organisational interoperability, enabling them to function together for inter-organisational synergy [84]. Many HRO rely upon how well teams operate together. Poor leadership causes doubts within teams. Firefighting relies heavily upon leadership to ensure teams work efficiently and to keep team members safe. Leadership is paramount to the success of HROs [84].

2.4 Naturalistic Decision Making

NDM [74] or Dynamic Decision Making [51] is often found in military, aviation and firefighting domains, where decision-makers are faced with frequent on-the-spot complex decisions that need to be made quickly considering the risks involved. NDM occurs in un-scripted situations and must be practised similarly when considering training environments [74]. Expertise, knowledge and strategy is necessary to handle NDM situations and there is a high reliance on frequent situation assessment and communications to make high quality decisions [76]. CRM is a strategy employed by numerous HROs to ensure high quality decisions are made and effective response takes place [36; 72; 84].

Aviation and firefighting tasks can both vary in physiological and psychological difficulty. A lack of adequate training in normal conditions can cause poor performance and occupational stress [130; 132]. Stress has a significant impact on the mind and body [89] causing irrational behavior, effecting decision making [107; 112] and fatigue [46].

One of the most crucial skills of AAS is the ability to make good quality decisions, while subjected to a high level of stress, generated from various channels: psychological, environmental and physical. Even the act of making the decision may elicit stress responses [131]. It is often concluded that stress has an effect on decision making ability as well as a physiological effect [131]. S.E. Wemm and E. Wulfert found that the presence of stress in high-risk occupations led to riskier decision making among males and that it also created a narrow view on possible outcomes or consequences of a decision [144]. Mosier et al. found that stress or anger in high tech environments led to information blindness and premature closure on a decision option [101].

Incorporating stress into a VRTS allows safe exposure to CIS for emergency and disaster responders in decision making situations, providing opportunities for stress resilience training [46] and embedding stress management into training. It is critical to understand what occupational stress has on responders and how we can utilize the stressors in such a way that we create better training outcomes through greater stress resilience [4; 46] or stress inoculation training [47].

Experiencing a severe situation that has an intense emotional or physical effect is known as Critical Incident Stress CIS, which can lead to Post-Traumatic Stress Disorder (PTSD) [106] and generally poor operator states. If too much stress is being experienced, excessive stress hormones are released [87], suppressing critical regions of the brain for higher cognitive function. This causes problems such as; behavioral problems like self-control [90], learning issues [95], inability to access stored memories [87], prediction errors [116], being unable to communicate effectively [29], being unable to make decisions [145], or can even cause a loss of motor skills [67]. Wildfires are known to have an effect on the cognitive, physical and physiological performance of personnel [54].

In order for effective decision making to take place in any complex NDM environment, a positive operator state should be maintained, so considerations must be made in training on how to manage stress and maintain a positive state. Operator states have an effect on risk perception and risk-taking behavior [104]. Negative operator states can be caused by the operational situations themselves. This may be a result of over exposure to information overload or helmet-fire; frustration with the task-work or equipment; witnessing fatalities or people in dangerous situations; a lack of food, water or sleep; and environmental effects

[104]. The compounding effect can create a long-term fatigue from excessive exposure to any of these factors [104].

2.4.1 Physiological Response

Physiology has been a key metric to determine a state of stress [89; 97]. Many cognitive and physiological responses occur when subjected to stressful situations including circadian functions [89]. Physiological effects can be measured objectively using Electrocardiogram (ECG) for HRV or detected in the brain using an Electroencephalogram (EEG) [27]. Meehan et al. found that HRV was a suitable metric for detecting presence in a stressful Virtual Environment (VE), designed to elicit fear of falling or vertigo [96]. They also found that repeated exposures to the same stressful VE diminished the physiological response [96], becoming acclimatized to the situation. Other physiological responses to stress such as cortisol, Galvanic Skin Response (GSR) or change in skin temperature were found to be more cumbersome or less reliable in terms of providing fast or accurate response to stress [96].

2.4.2 Neurological Response

Emotional states experienced by the operator such as stress and anxiety have been shown to have an effect on making good quality decisions [90]. Decision making relies upon a closely interlinked complex neural network and specific regions of the brain [25] known as the limbic system, cerebellum and Prefrontal Cortex (PFC) to respond appropriately to a given situation being experienced. This is done by active retrieval of encoded memories [90] and live processing of multi-sensory information [98]. The regions of the brain that govern emotional states and decision making are very closely linked and are regulated together [90]. It is critical to understand the occurrences in the brain (neurology) and body (physiology) during high-stress scenarios, what effects it has on our ability to make decisions as well as other cognitive functions. Understanding brain and body functions is an important factor that influences the AA VRTS design.

A set of neural substrates or subcortical structures are known for their involvement in decision making; the amygdala for emotions and memory, the thalamus for motor and sensory input and the cerebellum for fine motor control [25]. The limbic system, responsible for our emotions, motivation, learning and memory, is part of the core brain structures involved in decision making [90]. In the limbic system, the amygdala triggers a behavioral response based on memory and sensory stimulus [90]. Sensory stimulus is processed by the thalamus before being sent to the amygdala [25] with the exception of smell which bypasses the thalamus through the olfactory or first cranial nerve [45] and is encoded into olfactory memory [146; 148].

Stress and anxiety has shown to have an effect on the amygdala, a region of the brain that controls behavioral response [127]. If experiencing anxiety, the amygdala becomes hyper-responsive [90; 127] or excessively stimulated. Meanwhile, the ventral portions of the PFC becomes hypo-responsive or less activated, indicating inhibited executive function, such as decision making or behavioral control [90; 127]. Martin et al. concluded that the same area of the brain that handles executive function is controlled by the same regions which handle emotional response [90]. Repeated or excessive use of the region through negative emotional experiences can diminish the ability of executive function and cause increased error rate in behavioral response [90]. Gonzalez found that high task loads had detrimental effects on cognitive ability in dynamic decision-making environments with a greater effect on those with low cognitive ability [61].

A condition coined decidophobia [60], the fear of making the wrong decision, can cause further anxiety and delay in decision-making. This can unnecessarily trigger the fear network, inhibiting either motor or cognitive function [45]. Excessive exposure to stress can cause long term effects such as PTSD [77]. In risk-based decision-making situations, it is shown that stress is a state that causes riskier decision-making [144]. In terms of communication, a region of the brain called Broca's area which handles speech is known to become functionally and structurally altered after experiencing chronic or traumatic stress [31; 77], experiencing less blood flow which inhibits the ability to speak fluently [29; 57]. Additionally, another region of the brain known as Wernicke's area that is responsible for speech processing is also known to become impaired under stress [29], highlighting the link between stress, comprehension of verbal information and communication.

The cognitive region of the brain comprises of an area of the Prefrontal Cortex or the frontal lobe of the brain, where complex cognitive and behavioral functions such as decision making, problem-solving, planning ahead, self-restraint and acting with a goal in mind takes place [25]. The habenula is a pair of nuclei located above the thalamus and provides a fundamental role for survival and decision making [67]. It receives neurotransmitter signals from the limbic system and sends signals to the midbrain responsible for the release of feel-good chemicals such as dopamine and serotonin [67]. The habenula is also responsible for sleep and sleep-like behavior being co-located with the pineal gland, which is responsible for circadian rhythms such as heart rate and HRV. Stress resulting from overexposure can inhibit motor ability as well as behavioral function, due to the modulation of dopamine and serotonin release [67].

It is shown that decision making relies on multi-sensory stimulus as well as contextualized active memory recollection [126] where a quicker response time and higher performance decision making is achieved by combining relevant multi-sensory cues over a singular cue [98; 126]. According to Bizley et al., multi-sensory decision making works particularly well in noisy environments with multiple channels or sound sources [20]. (EEG) can be used to show activity in brain regions responsible for decision making in lab-based conditions [27; 98]. Mercer et al. discovered a faster response time for decision making with multi-sensory information [98].

This presented research highlights that stress has a major impact on how our brain functions, responds to immediate situations, makes decisions, comprehends the situation and also communication.

2.5 Presence, Immersion & Fidelity

In this section, we define the aspects of Presence, immersion with VEs and simulator fidelity to provide the reader with conceptual knowledge regarding virtual worlds and simulators. Although these three factors are somewhat different to another, they are seemingly used to describe VE interchangeably.

2.5.1 Presence

Presence is defined as being the subjective sense of experiencing a VE. Presence within a system is determined by the suspension of disbelief [129] or that what we feel inside the VE being experienced is real or a scale thereof. A sense of presence can be felt within a virtual world comparatively to what we experience in the real-world [133] based on our sensory system. Meehan et al. describe a sense of presence in a VE being related to stress or fear that can be measured objectively with physiology sensors [96]. However, they also discovered low stress environments would be more difficult to measure presence. Presence has been linked to a higher rate of skill transference from VR into real-world applications, such as firefighting [93; 129]. Increasing Presence within a simulation, increases engagement with the training content [17], leading to increase in time on task and potential skill acquisition, retention and task related knowledge [17].

2.5.2 Immersion

Immersion is described as the physical technology used to create an experience within a VE. It is often due to the sensory stimulus being artificially created to give the user a false belief that what they are experiencing is true, thus achieving a level of presence within the VE. The greater amount of sensory stimulus we provide further adds to the immersive experience, creating a more immersive VE. Having a sense of Presence within a VE is a good way to ascertain if a system has achieved a suitable level of immersion, creating the potential for greater skill transference. Seymour et al. [125] demonstrated that VR enabled skill transference from training to operating room environments with a 29% speed increase in gall bladder removal and lesser chance to fail or cause injury in the procedure. It is also possible that surgeons can obtain the physiological structure of a particular patient, to the degree that the information can be accurately reproduced in a virtual 3D environment. The surgeon can then practise operations on a specific patient, with a highly accurate replica of the patient, enabling them to practise specifically for the situation and have a greater chance of success [125].

2.5.3 Fidelity

Fidelity is often described in terms of being a physical or psychological experience of a system, however, many other subcategories of fidelity exist [54]. We explain these categories below. Fidelity is fairly loosely defined and is comprised of numerous aspects or dimensions. Some of these dimensions overlap with one another in order to emphasis the effects and create a greater overall training fidelity [64].

2.5.4 Simulation Fidelity

Simulation Based Training (SBT) is regarded as training which utilizes full mission simulations to replicate a complex environment, complete with a pre-briefing, to discuss the situation at hand and potential strategies to handle it [133]. Case studies, role playing, part task trainers and full mission simulation all make up different levels of fidelity of SBT. Situations can be repeated accordingly, with trainees exchanging roles to obtain more training experience. A post-training analysis of the simulation provides valuable lessons from each member and also instructor feedback [18]. Commonly, physical fidelity is compared to psychological fidelity as the two most significant dimensions in terms of low and high fidelity [133].

2.5.5 Physical Fidelity

Physical Fidelity is the most often discussed aspect of fidelity [86], often described in terms of visual fidelity but also encompassing several other dimensions including auditory, vestibular, olfactory etc. which make up the physical aspects of a simulator [17]. For example, in an aircraft or helicopter cockpit, providing an enclosed area with the typical gauges and instrumentation would be considered a minimum requirement for physical fidelity. Passive haptic interfaces have shown to have a positive effect on presence in a VE [96], providing a subtle connection to the VE often through vibro-tactile feedback. Passive vibro-tactile feedback can give the illusion of engine vibration and turbulence.

2.5.6 Psychological Fidelity

Many people consider psychological fidelity to be the most important aspect of training [18; 133]. Emotions such as stress or satisfaction being experienced by a VE equivalent to the real world is considered to be the psychological fidelity [86]. Without psychologically stimulating training, the training is not focused on specific outcomes, ultimately becoming non-stimulating, lacking the engagement required for skill development [17]. Psychological fidelity is regarded as how a VRTS elicits cognitive, behavioral, and affective responses in a situated environment [133].

2.5.7 Functional Fidelity

Function fidelity is the extent to which the simulation, the devices and virtual objects respond accordingly to the real world equivalent [86]. An example of this in an aircraft or helicopter simulator would be how the radio and gauges respond to receiving transmissions and changes to the flight dynamics like altitude. Functional fidelity can impact the skill or knowledge transference [17], making it important to accurately replicate real-world expectations. To provide the best training experience, all of the normal tools that are required to use in the real world would be best to be accurately replicated [17]. Enabling normal functionality from devices such as radios, creates a greater familiarity with the expected behaviors and usage protocols during training.

2.5.8 Interface Fidelity

The tools we would normally find to conduct tasks in real-world situations have an effect in creating a functional virtual interface. By utilizing realistic tangible interfaces, we create better learning environments for things like muscle memory and understanding what button to press to achieve a certain goal or task, increasing the functional fidelity of the system [17]. For example, in radio communication users must use the push-to-talk (PTT) switch to begin a transmission. By pressing the PTT button or a footswitch in some aircraft enables the device to transmit a verbal message to other emergency responders. Since this is an existing interface, it would be useful for operators to have the same style of interaction in a simulated experience to improve the engagement and functional fidelity, engagement and potential skill transference [86].

2.6 Virtual Reality and Simulation Based Training

Many attempts to create training systems for stressful occupations do not focus on the psychological aspects of the user needs [133], but more on the technological advancements often missing the needs of the user, leading to rejection of the technology [33]. Straus et al. conducted SBT, a study within the US Army and discovered mixed user responses to SBT and highlighted the importance of psychological fidelity in SBT [133].

Simulator technology and using VR for training has been around for decades in many high-risk occupations, particularly in aviation, surgical procedures, military use and also in emergency response domains such as firefighting [147]. Air Attack is a unique crossover of aviation, firefighting and using military-like strategy and tactics.

Virtual simulation has been shown to be beneficial to the expert domain, involving high levels of cognition, complex decision-making situations or NDM [133]. This is due to the degree of psychological and physical immersion that can be achieved with the technology and the repeat-ability of complex situations in a safe training experience [133]. However, the level of expertise must be considered when designing VRTS for complex environments as novice users are often overwhelmed by stimuli, whereas expert users require additional stimuli to maintain engagement [133].

Simulation has been the preferred method for training complex tasks without any collateral damage or loss [133]. It offers high-risk training for nearly any situation possible. Aside from performing the real task, simulated training can more effectively translate the mental stress of the situation, as well as offering repeat-ability at very minimal risk to the trainer. Bouchard et al. found a significant relationship with presence and anxiety [24] in VR. This suggests that if we want to maintain a certain level of Presence, then the simulator must provide an adequate level of stress for it to be engaging.

A simulator can provide direct control over the training conditions and can enable greater task rehearsal [110]. Having access to cheaply reproducible training content can drastically increase the turnaround time to train new recruits but also give trained firefighters the ability to maintain their skills and create cognitive muscle memory. For these reasons, simulation training is the preferred method of training for many high risk occupations, such as aviation simulation, air-traffic control, military training and emergency response services.

Providing the exact devices, replicated tools, software etc. within a VE, affords the user with the ability to gain more familiarity with the tool usage within a situated learning environment. This is crucial in an NDM environment. Traditional aviation simulation requires a physical replica vehicle cockpit, based on a particular aircraft. While this has a large benefit of allowing a user the feeling of being inside a real aircraft cockpit, the installation costs, upkeep, maintenance and scale of this type of system does not make this technology widely available and requires dedicated space. The cockpit cannot be easily swapped for a different type, as it is effectively a semi-permanent system. HMDs enable an immersive VR experience for training and easier to set up and pack down due to its portability. This is beneficial for teams and organisations spread out across a large area. The cost for such a device is more affordable and can be easily distributed, enabling more frequent training opportunities [133]. The use of VR HMDs has changed how computer SBT can be experienced, by completely isolating the user within a computer generated highly visual and audio environment, and blocking out the real world. The VR content can be changed and modified to suit any application.

Existing literature suggests that while the fidelity of simulation technology is highly immersive in terms of the physical fidelity, psychological fidelity is often overlooked, causing the training experience to be misdirected and a poor outcome from using the system [133]. It is important to consider psychological immersion, in order to improve the presence of the simulator.

Lee et al. [79] state that simulators are a common way to train novice pilots on how to handle large expensive aircraft without exposing them to the stress of operating such complex systems in the real world. Simulators are also used as a way to maintain individual abilities, to ensure that the skills pilots have obtained are maintained or current and up-to-date by managing their skill currency [21]. Complex tasks such as decision making in flight, where pilots must react to a problem such as engine malfunction, or a potential in air collision need to be memorized by practice and experience. Other high-level cognitive tasks such as gaining SA through radio communication can be practised in SBT to gain proficiency.

VR has been used for training in firefighting to great effect [69; 80; 119; 137]. Firefighting relies upon situated training events to ensure that firefighter skills are maintained and current. Most often, training for firefighting has a high physical demand, acrophobic tests, claustrophobic and other mental aptitude tests. It often involves the handling of dangerous equipment that, if used incorrectly, can cause user harm. These aspects are considered to be of high psychological fidelity, the essence of which we need to maintain in our proposed simulation system, in order for it to be effective according to [133].

In SBT, it is often falsely understood that greater realism regarding the physical fidelity of the system creates better results. However, contrary to this belief Beaubien et al. [18] found this not to be the case, finding no direct relationship between the level of simulated fidelity and teamwork skills training. Training systems must focus on the psychological stimulus for them to be effective.

SBT is used extensively in the military with a wide range of fidelity to train groups or units of soldiers to learn and show proficiency in team-based activities vital to conducting successful missions [133]. Known as collective training, military personnel practice in group activities to build and maintain individual skills. Collective training is crucial to the U.S. Army to maintain readiness and combat effectiveness [133]. Military and firefighting share many physical and psychological occupational aspects such as loss of life, injury and other stressful situations, rapid decision making, operating in harsh conditions and under extreme danger, as well as expected to perform a variety of duties and tend to many different situations, carrying a large cumbersome kit. Both organisational structure is based on a chain of command.

SBT is such a technology that supports the doctrine of network-centric warfare as it allows soldiers to practise protocols and procedures in team-based settings, establishing the level of expectations when using the tools. Even scenarios where equipment failure may occur can be practised so that response plans can be adequately prepared and executed. Simulation fidelity has been widely studied within military exercises and can be often described in terms of psychological fidelity and physical fidelity [133].

2.7 Training for high-risk Complex Environments

Many high-risk occupations must be trained for, in order to be successful. Novice trainees must be exposed to situations that replicate the conditions that they would normally experience in order to become proficient in the task. This can either be done in live training or performed virtually. Complex environments normally carry an amount of risk which can be replicated virtually with a variety of fidelity, providing a safe and effective learning experience. When training for risky situations, we must be careful how much stimulus is presented at different levels of expertise, as it is shown that too much physical fidelity can overwhelm a novice, but a higher fidelity is required for an expert to become more proficient at a higher level [65].

Straus et al. state that novices are overwhelmed by too much sensory stimulus, inhibiting their ability to learn from high-fidelity simulators [133]. Although the amount of stimulus they may be exposed to is equivalent to what they would experience in a real situation, being directly immersed in a high fidelity simulator experience can over-stimulate novice users, inhibiting their ability to learn from the system [62], making it important to consider when training for a complex environment. Complex environments which naturally are deeply embedded with psychological and cognitive functions such as hazard awareness, can be built into training programs [108].

Air Traffic Control (ATC) is a high-risk occupation, where the mental demands are primarily around ensuring that the aircraft in the airspace they are operating over, are in safe proximity and also ensure they land and take off safely without collision. A study performed by brookings et al. showed an increase in physiological behavior such as respiration rate and frequency of eye blinking of

ATCs when placed under overwhelmingly stressful situations [27].

Balancing the stresses of being responsible for people's lives while avoiding airspace catastrophes carries a high degree of stress on ATC emotional state [101], especially if they are handling complex or challenging situations. It was shown in a simulated training environment, when facing an overwhelming amount of free flyers, ATCs would give up in the practice environment due to cognitive overload. This is due to the overstimulating demand in psychological taskwork.

The level of expertise of a trainee can determine the effectiveness of the physical or mental fidelity in the simulator technology [70]. For example, in a flight simulator a novice trainee may be entirely overwhelmed by all the components of a fully equipped simulator [62] with multiplexed radio channels to experience the intense communication and decision making tasks. At the other end of the scale, an expert would benefit more from the training experience if all of the extra sensory cues and information flow experienced in the occupation were present in the simulation [65; 133].

Complex environments usually comprise of team-based situations, where people are relying upon others to achieve a goal [80]. It is crucial to their effectiveness that leaders and teams practise their roles together due to the large reliance on teamwork [34; 133]. This is critical for the development and maintenance of operational readiness. This is to ensure that when they are faced with a real danger or situation, they will collectively be more confident to make better decisions under high pressure situations [80]. By practising together, skills such as shared or distributed SA can be developed [34].

High risk industries such as health care, firefighting, military or aviation are dependent on SBT for training teamwork skills [18; 133]. Emphasis on psychological fidelity is highly important, otherwise trainees may become disengaged [63; 133]. The level of simulator fidelity is important to consider for the level of expertise of a trainee [63; 133]. More complex simulations can overwhelm novice trainees, while experts need the extra fidelity to maintain engagement.

VR has been used for training in firefighting to great effect [69; 80; 119; 137]. Firefighting relies upon situated training events to ensure that firefighter skills are maintained and current. Most often, training for firefighting has a high physical demand, acrophobic tests, claustrophobic and other mental aptitude tests. It often involves the handling of dangerous equipment, that, if used incorrectly, can cause user harm. These aspects are considered to be of high psychological fidelity, the essence of which we need to maintain in our proposed simulation system, in order for it to be effective according to [133].

Chapter Summary

In this chapter, the air attack domain was presented along with the related fundamental aspects pertaining to the effectiveness of SA, communication and CRM and NDM. Related VRTS information to VR and SBT was also discussed. We discussed how stress elicits neurological and physiological responses and behaviour, then explored how SA, decision making and communication ability as higher cognitive function is effected under stress. Aspects regarding VR and simulation, presence, immersion and fidelity were discussed in relation to training in complex domains.

We have described the current state of the art and techniques used in other high risk domains around the use of SBT. For surgeons, it is important to practise frequently with the tools they would use normally in an operation and have an accurate replication of the patient, enabling them to pre-train for the real patient [125]. This provides a better success rate in real-life surgery. Military are often using simulation so that they may be prepared for situations they may be exposed to in the field. Aviation sectors use simulation to gain a certain level of experience flying certain complex and costly aircraft before they can fly one in the real world.

The research in this thesis fills the gaps in simulation training in complex environments, as very little research exists on VRTS for aerial firefighting, making the content of this thesis novel and a valuable contribution to the research domain. Although this research is specific to AAS, other complex team-based domains can benefit from the content of this thesis. The content presented provides an in-depth understanding of the requirements for designing user-centered prototype VRTS for AAS, which is presented in the next chapter. Chapter 3 begins with an initial user research investigation, an initial prototype design followed by two iterative design cycles. This presents the user requirements for training and the design iterations made from user feedback with the prototype VRTS. Chapter 4 presents the details of the individual research studies designed around SA (Section 4.1), Communication (Section 4.2) and Decision Making (Section 4.3) with the user experience of each of the experiments that were performed after each stage of the iterative design cycle.

Chapter 3

Methodology

This chapter describes the development of the prototype Air Attack (AA) Virtual Reality Training System (VRTS) following the UCD methodology, presented in Section 1.5 of the introduction. The AAS context of use was defined previously in Chapter 2, which now leads to the next phase of the design process; specifying the user requirements. Firstly, the findings from the end-user research are presented in Section 3.1 which includes focus group discussions, Subject Matter Expert (SME) interviews and observational studies performed during classroom and field training exercises. Section 3.2 describes the technologies used to implement the system to create the VE; the computer software and hardware, the sensory experience including the display types, audio and haptic feedback. The fire events and locations that were re-created for the simulation are also presented. Section 3.3 provides the measurements used for evaluating the prototype VRTS, then finally Section 3.4 describes the design iterations, which were used for each empirical study, which is presented in Chapter 4.

3.1 End-User Research

An initial user-research investigation was conducted to capture detail, desires, needs, requirements and workflows of the end-users. Three SME were directly interviewed regarding their air attack experience and training recommendations. These questions are provided in Appendix A.1, with the details of this investigation provided below. This information along with the background research presented in Chapter 2 provides a starting point to design a user-focused VRTS for AAS in training. The main findings were that leadership, stress management, SA, communication and decision making are all important factors for AAS. This critical review provided the foundation for our purpose-built immersive virtual training simulator which focuses on the latter three. Air Attack is a subset of the firefighter chain of command. The following sections are the synthesis of the end-user research.

User feedback and responses regarding their training experience and the major concerns about their role were acquired through multiple methods outlined in the following sections. The identified end-users of the system are shown in Table 3.1.

Table 3.1: End-users for the Air Attack Virtual Reality Training Simulator.

End-User	Description
Air Attack Trainer	Senior firefighters with decades of experience in both firefighting as well as aviation and disaster response. Being an aviation firefighting specialist, they are SMEs, having many previous aircraft flying experience, they understand a lot about the aircraft environment through many years of operational experience. Age of 65 and 23 years experience in aviation firefighting. More information about this user is provided in the semi-structured interview in Section 3.1.2.
Air Attack Supervisor (AAS) trainee	The AAS is a highly experienced expert firefighter, with an average of 20 years of experience fighting wildfires, with three years service on average in the AAS role. Must have prior ASS experience (see ASS trainee). Predominantly male, with an average age of 47.
Air Support Supervisor (ASS) trainee	Also an experienced firefighter with fifteen years on average fighting wildfires, with nine years on average in the air support role. ASS are naturally selected to become AAS due to familiarity operating around aircraft. Predominantly male, 46 years of age on average.
Aircrew: Helicopter & fixed-wing aircraft pilot	Although not a primary end-user, pilots should be considered as a secondary end-user as they are a part of the response and have a valuable contribution. It is important to include them in the training process where possible to practise CRM. AAS trainees can get familiar with the pilots in VR as they would be potentially working with them in a real life response. Pilots have a specific radio protocol which trainees must also become familiar with.

3.1.1 Focus Group

A focus group was held with fifteen AAS trainers and trainee end-users (Table 3.1) where they were asked what aspects make a good or bad AAS. This identified the areas which need to be focused or improved on, contributing to the user requirements. This group discussion was conducted by the AA trainers mentioned in Table 3.1. The author of this thesis was present but predominantly let conversations between the group to take place while taking notes to allow the natural flow of thought and ideas to develop organically between SMEs and the trainees. By doing this, it allowed the researcher to experience the discussion from the point of view of the trainee, and to empathise with the group using a research lens. The researcher's objectives in this case were to take notes and learn along with the trainees.

The behaviors that were identified by the AAS cohort are listed in Table 3.2 and split into two polarising categories, good behaviors and habits that should be reinforced, and bad behaviors that should be identified and corrected by focusing on them in training. In the group discussion, when AAS were asked about what they considered the fundamental aspects of the role, the group identified the following four key principles: communication ability, decision making, confidence and SA.

Table 3.2: Good and bad behaviors that were highlighted in the focus group.

Good behaviors to practise	**Bad behaviors and skill gaps**
✓ Understanding tactics	✗ Being too focused on minor details, missing the bigger picture.
✓ Good documentation	✗ Communications confused or obfuscated.
✓ Good CRM	✗ Not knowing when to stand down helicopters when a fixed-wing aircraft is approaching.
✓ Established early high quality communication	✗ Slow to get aircraft into tasks with clear communication.
✓ Assessment of fire environment	✗ Mixed instructions between different groups.
✓ Good briefing	✗ Poor SA - potential conflict/lack of knowledge.
✓ Understanding of HRO principles	✗ Poor delegation to ground crew.
✓ Hazard identification	✗ Lack of detail to crew.
✓ Enacted Safety, Effectiveness, Efficiency & Logistics SEEL directives	✗ Low levels of confidence in decision making, delivery of briefing and communicating intent.
✓ Good situation reporting	✗ Slow to change in a fast moving environment.
✓ Good listening skills	✗ Slow decision making.
✓ SA quickly established	✗ Inability to keep two steps ahead of the problem.
✓ Team player	✗ Poor prioritization.
✓ Good decision maker	✗ Indecisiveness.
✓ Good at delivering their intent	✗ Failure to drive decisions down to where they are needed.

3.1.2 Semi-structured SME interviews

Three AA SMEs from Fire and Emergency New Zealand (FENZ) were invited for individual interviews. The SMEs have been training other firefighters for aviation-based firefighting for an average of 18 years. The interviews were performed by the author of this thesis and a post-doctoral researcher. One of the researchers primarily took notes while the other researcher led the interview questioning and discussion. The semi-structured nature enabled the SMEs to speak their mind on important issues, whilst allowing the researcher to guide the flow of the conversation. The interviews were audio recorded for post-interview analysis and the responses were thematically encoded into the following subsections.

3.1.3 The skill set of an AAS

AASs require a variety of skills such as leadership, knowledge, discipline, resourcefulness and communication ability. Additionally, they must possess personal attributes such as mutual respect, humility, courtesy, fairness and other interpersonal relationship skills. On top of these interpersonal skills, they need to be able to identify fire behavior and manage the flow of information.

3.1.3.1 Crew Resource Management

AAS must actively communicate with and listen to the advice from operations management, in order to get a better understanding of the overall picture and to maintain SA. They must think on a team level, understand the concept of CRM and utilize the skills and knowledge of the crew to solve problems. They need an ability to coordinate and communicate within the command structure such as operations on the ground, then tasking crews and overlooking the operations to see if the objectives are being achieved.

3.1.3.2 Leadership

AAS needs to understand battle-rhythm - how an operation is taking place, looking for signs of complacency or fatigue. They need to encourage others to question decisions and to discuss emergency response strategies in down times or when appropriate. AAS needs to describe what the end goal of the aircrew is and what Air Attack is expected to achieve as a part of the operation. They need to make their intent understood well by others and focus on producing team synergy. If their intent is vague or unclear, this can cause operational friction within the team, reducing their effectiveness and trust in the leadership. AAS can be effective crew leaders and enable their aircrew to perform efficiently in stressful conditions. They must utilise the skill sets and resources of the group, their shared tactical knowledge to build up SA and make good decisions.

3.1.3.3 Situation Awareness

Loss of SA is not an option in this line of work and for any HRO. Loss of SA can mean the loss of a life due to putting aircrew at the risk of unknown circumstances. To build and maintain SA, AAS need to ask themselves questions such as *"What does my team know that I need to know?", "What do I know that they need to know?", "What does none of us currently know that we all need to know about?", "What are we not paying attention to?", "Are we working effectively?", "Is everyone looking at the same thing or are we splitting our resources effectively?"* AAS must manage the aircrew SA by probing for information and feeding it back frequently.

3.1.3.4 Self Awareness

AAS needs to be self-aware and communicate their own limitations as well as recognize any diminishment in their ability and capacity to make decisions within a

NDM environment. They need to recognize aspects such as; fatigue, inability to communicate, inadequate SA, becoming complacent, lack of teamwork or available resources, stress and anxiety or lack of assertiveness. They need to know when to pull out of the situation and take a different look at the environment and the fire behavior.

3.1.4 Observational Studies

Classroom-based and field training exercises were observed, identifying the differences between both types of exercise, the level of stress and what kind of stress trainees experience. This was done in order to get a better understanding for the occupation and the training objectives. A significant difference between the classroom radio role-play exercises was noted. The radio role-play was considered to be a low-physical and high-psychological fidelity simulation, where the field training exercises were of high or perfect physical fidelity. It was clear the effect the perfect fidelity environment had on users, having to operate around real machines. This forced the trainees to be more engaged in the training and have greater SA so it would be best to replicate these effects where possible.

3.1.4.1 Classroom observations

In addition to the radio role-play exercise, there was also a comprehensive bookwork regarding critical aspects and occupation with problem solving writing exercises. Calculations and reading material included content about fire spread behavior, aircraft types, CRM, water capacity and fuel cycles. Presentations were provided about previous fires as well as videos from other situations not particularly specific to firefighting but also in military situations, leadership and communication. Discussions and questioning from the trainers were frequent after each video to ensure the topics are embedded into trainee working memory. To capture the high-cognitive aspects of the job, radio role-play exercises were conducted to simulate the occupation stressors such as NDM situations, *helmet-fire* and to practice CRM techniques as well as fuel and fire retardant calculations covered in the book-work.

3.1.4.2 Field observations

Field observations were made on six occasions from a nearby vantage point on the ground close to the simulated fireground, see Figure 3.1. We observed how the aircrew works together in concert to drop water on the target, represented by orange traffic cones for the fire line. The aircrew attempts to make a 20 percent overlap from the previous drop, to ensure an effective coverage of fire suppressant. Cones were shifted to make it more interesting for the pilots, who must use their imagination about the fire. Depending on the cohort (AAS or ASS), trainees would be rotated around as the Operations Manager (OM) (Figure 3.6), filling crew for helicopters and fixed-wing aircraft (Figure 3.2), performing AAS and relocating cones (Figure 3.3).

3.1.4.3 AOP back-seat observations

The researchers were invited to observe five training exercises in three different locations; Rangiora and Alexandra (Figure 3.5) in Te Waipounamu (South Island), Napier (Figure 3.1) in Te Ika-a-Maui (North Island) of Aotearoa, New Zealand. Observations in the backseat of the AOP took place three times, twice in Rangiora and once in Napier (Figure 2.3). It was important to be a passive observer in the AOP back-seat (see Figure 2.3) without impeding on the exercise. This was to experience unbiased radio communication and interactions between the AAS, aircrew pilots and the AOP pilot. This also provided a greater contex-

Figure 3.1: A live field training exercise being conducted in Napier. Two bucketing helicopters operating in the background. The AOP helicopter is refueled in the front with AAS trainee being debriefed by the SME.

Figure 3.2: Water refill stations being managed by trainees, Left: fixed-wing aircraft. Right: Portable/collapsible water dam for helicopters.

Figure 3.3: Firefighters relocating cones for simulated fireline.

tual understanding of the radio cockpit environment as well as experiencing how the helicopter performs advanced maneuvers in the air. We observed the aircrew pilots from the elevated position performing their aerial drops to experience the working environment from the trainer's position (Figure 2.3).

The trainer is seated in the back with the trainee AAS in the co-pilot seat. From this perspective, the trainer gave an appreciation of the training exercise. The trainer can make easy observations about whether the classroom material has been transferred to real behavior, i.e., the methods and behaviors that the trainee is employing to achieve their tasks. The trainer can give quick feedback and suggestions to the individual trainees in-situ, calling them out on poor handling. This close-quarters training is essential for the trainer's intent to be successfully delivered to the trainee. The trainer is also able to reiterate the points they have mentioned, or any common themes or patterns emerging from the training cohort in post-training debrief.

Figure 3.4: AAS being briefed by the AOP pilot at the Rangiora airport.

3.1.4.4 Differences between Radio Role-Play and Field Exercises

During the radio role-play session, the experience could be described as a low-fidelity simulation using actual radios and was a re-enactment of a fire scenario. Trainees act as pilots, ASS and AAS performing CRM tasks and having to make decisions and calculations on the spot when the trainer makes requests on the radio, known as a *radio inject*. The radio inject is usually of the type which forces the trainees to make logical decisions rapidly. If the trainer is not comfortable with the rate at which the trainee responds, they make additional radio injects, so that the trainee quickly feels under pressure as the number of tasks and conversations they need to manage simultaneously becomes compounded. The trainer maintains the state of stress being experienced by the trainee using radio requests for information such as a *recce* or situation report (sitrep), remaining fuel time of the aircrew and water availability from the ground crew. Also present in the

Figure 3.5: A field training operation at the Alexandra Airport for ASS trainees.

role-play was a constant background radio chatter from a real fire event which provided a realistic situation experience, as voices and conversations related to the fire take place, adding to the immersion of the simulated role play.

In comparison, in the field training, which could be considered as true-fidelity with a high degree of functional fidelity, there was no actual fire involved and did not reenact a fire event, so it lacked an element of psychological fidelity that is normally associated with the role. Additionally, there was no live radio injects or background chatter pertaining to the situation, reducing the psychological complexity. Instead, the field training focused on the operational elements like setting up flight paths or circuits, and figuring out drop heights and water coverage with AAS trainees providing feedback to pilots. Trainers in this case would sit behind the AAS in the AOP and question the trainee on their actions (or inaction). Field exercises had enough of the physical elements and the very real threat of danger

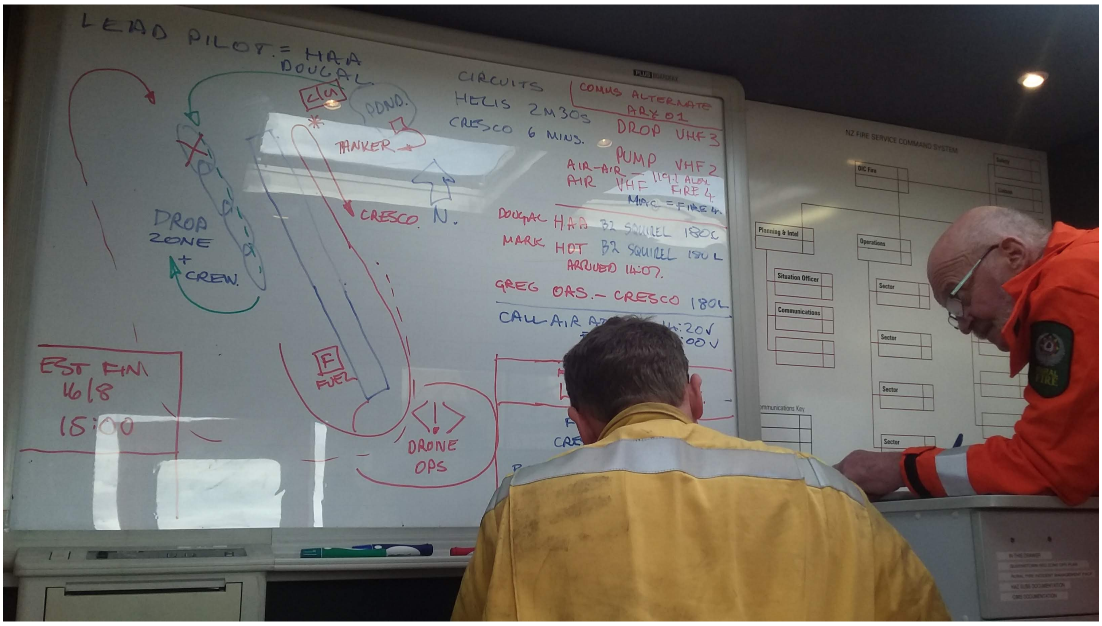

Figure 3.6: An ASS trainee in the incident command post acting as OM.

of operating around aircraft. Creating excessive helmet-fire in this case (as experienced in the radio exercises) would generate a potential risk to the trainees and aircrew.

Field exercises are generally run the day after classroom exercises to put the material from the class into practice, where the trainers can judge if knowledge was successfully transferred. This is necessary to find out if the trainee meets the criteria for real-world deployment. Radio exercises take roughly half a day and cater for roughly between twelve to twenty trainees. Field exercises would take the whole day and cost a comprehensive amount, mostly due to aircraft operational costs like fuel and pilot time. In both cases no real fire existed, requiring trainees to use their imagination. This reduced any real threat of fire danger which is experienced in a real wildfire event.

Figure 3.7: ASS trainees being briefed on helicopter operations protocol by pilot. Alexandra, New Zealand.

Initial User Research Summary

The user research we have presented in this section along with the background literature research was utilized to understand the context of use, and to specify user requirements to inform the research design.

The presented information clearly shows how it is essential for AAS to operate with leadership, emotional intelligence and encourage high inter-organizational synergy. The AAS active skill requirements are:

1. To quickly gain and maintain SA constantly.
2. To build and maintain high quality communication using CRM.
3. To use the information gained to make decisions, using the communications to command their intent to the aircrew efficiently and effectively.

In addition to these active skills, AAS must be self-aware of their own abilities, must be confident in their actions, showing their leadership and drive their decisions down to the aircrew effectively. For an effective simulator design, these aspects must be considered and integrated into the design process. Practicing the active skills in a NDM training environment provides support for each of the passive or soft skills such as leadership and confidence to manifest. With this in mind, the AA VRTS design and experimentation is tested against the three active skills.

With the user requirements specified, the VRTS design stage could take place as specified in the UCD model in Figure 1.4 from Chapter 1. In the next section, we define the various technologies used to build the experimental environment.

3.2 Simulator Environment

In this section, the various elements of the VRTS specifically for AAS training following UCD research and development are discussed. First, the software and hardware components that are used to create the VE are discussed and how the existing radio role-play exercise and training material was integrated to create psychological stress. Finally, the three simulated conditions that were developed are presented with system diagrams showing how the system was constructed and evolved over time with iterative development.

3.2.1 Virtual Environment

This section describes the VE that was replicated in the VRTS. The VE of the system is based on a rural forest environment in Aotearoa, New Zealand, although any place on earth can be effectively created as a VE. Historical fire events were used that had taken place in a variety of regions in both the North and South

Islands of New Zealand to provide context to the training. These locations were able to be accurately recreated using flight simulation software [91] and plugins that enabled photo-realistic scenery, described further below.

3.2.1.1 Computer Software

The software used to create the VE for the training scenarios is a flight simulator engine from Lockheed Martin, Prepar3D (P3D) [91]. This software was used to create a visually accurate representation of the rural forest conditions and enabled the visual sensation of being in a helicopter cockpit (see Figure 3.8). P3D can be modified and extensions to the source code can be made using an SDK. It also runs in all immersive display types. Software plugins were used to enhance the visual quality and allowed aerial firefighting techniques to be practised. Plugins such as Lorby FirefighterX [83] and Lorby Wildfire Response[1] were used to enable lifelike and dynamic fires with smoke effects, water-bombing functionality and AI aircraft. Lorby Wildfire Response provided a more intuitive interface and a much greater ability to create structured scenarios tailored towards aerial firefighting in comparison to the default P3D scenario editor, allowing better placement and removal of objects and fires in real time, complete with a library of 3D models and fire effects. This software also allowed the ability to download live fire behaviour from an active wildfire for visualisation and live training purposes. Additionally, to improve the visual fidelity of the simulation, photo-realistic scenery add-ons from FTX Orbx[2] were used to enhance graphical realism. For the CPD based system, the frame-rate was limited to 30 frames per second (FPS) to maintain system stability. Whereas to run the simulation software inside the Oculus Rift HMD, special software called Fly Inside[3] was used as it created separate CPU

[1] https://wildfiretrainingsolutions.ca
[2] https://orbxdirect.com/product/nzsi
[3] https://flyinside-fsx.com/Home/AddOns

Figure 3.8: Screenshot of simulator VE, re-enacting the Port Hills fire.

threads for the Prepar3D engine and for the VR HMD, enabling the HMD to run at a constant 90 FPS, to reduce simulator sickness [73].

3.2.1.2 Computer Hardware

A reasonably high-end computer was used to drive the system due to the graphical demand of the flight simulator software and photo-realistic scenery. Computers with the following specifications were used for Experiments 1 and 2: Windows 10 PC with 7th generation core I7 processor, 32GB of RAM, 256GB SSD primary hard drive and an Nvidia 1080 Ti 12GB graphics card. For Experiment 3, the computer was upgraded to an 8th generation core i7 with 64GB RAM and Nvidia 2080 Ti 20GB graphics card to handle extra graphical demand.

3.2.2 Physical Environment

In order to reproduce the physical experience, a vibrotactile haptic feedback bench seat was engineered (Figure 3.11). The seat also went through design iterations.

Foot platforms were added after Experiment 2 because the seat provided vibrotactile feedback through the body, but not through the legs and feet, which would be a closer experience to being inside a real helicopter. Doing this gave a more realistic, full-body experience. A pair of audio transducers were supplied by Earthquake Sound model Q10B[1] and mounted to the underside of the bench seat. The bench seat was sound isolated from the floor to ensure vibrations would pass through the participants and not disturb the surrounding equipment such as the projectors.

3.2.2.1 Visual Environment

An array of display technology was used and compared for suitability in the VRTS. Basic monitors were used in supporting helicopter pilot aircrew roles and additionally as part of Experiment 1 as a control group. HMDs were also used as this was considered to be the preferred solution, due to portability and quality of immersion. The HMD that was used in experimentation was the Oculus Rift CV1, to give the user a sense of accurate head tracking, stereoscopic rendering, with a display resolution of 1920x1200 at 90Hz per eye. The 270° CPD used was a SimPit Centurion with a 2m tall and 2.7m radius display surface, using three Acer Predator Z650 projectors, combined to create a 5760x1200 resolution at 120Hz to display the virtual imagery.

3.2.2.2 Audio and Haptic Environment

A Logitech 5.1 surround sound system was used to provide the auditory environment of a helicopter which was predominantly a droning rotor and engine noise as it is experienced in a helicopter. This was also channeled through to the vibrotactile seat shaker system. Since this sound is effectively ubiquitous, it

[1]https://www.earthquakesound.com/index.php/en/gaming-simulations/gaming-products/tactile-transducers/item/q10b

was not necessary to create spatialized audio. The sub-woofer provided further low-frequency sensation in addition to the haptic feedback.

3.2.2.3 Radio Communications

A mixture of physical hardware and computer software was utilized to create several communication channels. Off-the-shelf CB handheld radios from Uniden[1] were used to give an authentic radio experience for the ground crew to communicate with the AAS. The aircrew utilized a separate radio environment using Voice over IP (VOIP) communication software [134] to create an isolated aviation radio environment that could be manipulated to recreate radio problems normally experienced in the real world. This software was used to modulate voices to give a realistic radio sound, as well as cause radio transmission faults and provide static background radio chatter. Transmission failures would occur by periodically disrupting transmissions in software, to force users to establish methods to overcome these problems.

3.2.3 Experimental Simulated Training Environment

An existing technique, used in New Zealand rural wildfire aviation training, is to take an existing fire that took place and build a semi-structured scenario around this using pre-recorded radio injects about activity on the fireground and air base. The radio environment consists of two rooms used to separate and isolate trainees, with radio chatter extracted from the fire event played in the background to create a situationally relevant stimulus. In this situation, the firefighters will role-play certain key characters to create empathy and attempt to manage the emergency radio traffic. This simple technique is effective enough to create the psychological stress and the sensation of *helmet-fire*. For the first experiment on

[1] https://uniden.co.nz/product/uh820s

SA, three historic rural fire incidents were re-created. The first was a fire from Aoraki (Mt Cook) (January 2008) [41] in the McKenzie country, the second from the Port Hills fire [44] (February 2017) in Ōtautahi (Christchurch) and finally the Onamalutu Valley fire [6] (February 2015) in the Marlborough region (Te Waiharekeke), all of which were located in Te Waipounamu, the South Island of New Zealand. For the communication and decision making experimental studies, an existing radio role-play scenario has been used for FENZ AAS training was based on another historic fire incident known as the Gold Creek Fire in October 1997 (see Appendix A.3), located outside of Napier in Te Ika-a-Maui, the North Island of New Zealand.

3.3 Measurements

In order to answer the research questions posed in Section 1.4.2, we recorded both qualitative and quantitative responses in each of the three experiments. We used the following validated questionnaires:

1. The Igroup Presence Questionnaire (IPQ) to measure subjective presence in the virtual system [114].
2. The Dundee Stress State Questionnaire (DSSQ) as well as the short version (SSSQ) for measuring subjective stress state. [35; 94]
3. The Simulator Sickness Questionnaire (SSQ) to measure subjective feelings of nausea or other symptoms of simulator sickness [73].

The Situation Awareness Global Assessment Technique (SAGAT) was used to assess SA [51] in Experiment 1. Open-ended questions were used in all experiments to acquire qualitative data. To collect additional data about the participant stress state and to find any observable changes to participant physiology, HRV and breath rate were recorded with the Zephyr Bio-harness chest strap[1].

3.4 Development of the Air Attack Virtual Reality Training System

In this section, the different stages of the AA VRTS prototype design are presented. Following the UCD methodology, a simple environment was designed and tested for usability and further developed with end-user feedback as we progressed through answering our research questions. At each stage of the prototype design, further user research investigation regarding the critical aspects of the AAS role was conducted. Using the knowledge gained from each experiment through observation and user feedback, the system was developed based on the iterative design cycle, and evaluated against the user requirements before conducting further experimentation and design iterations. This process ensured the system was built with the user's end goals in mind, preventing unnecessary or poor development decisions. In the rest of this section, the system design is presented for each experiment. Experiments were designed to focus on the core active skills of SA, communication and decision making, fundamental to Air Attack and the end-user requirements.

Please note that an in-depth presentation of each of the individual experiments is given later in Chapter 4. Here, we present the design methodology, so the reader can better follow the logic of our process, without being overwhelmed by the details, which are presented later.

[1]https://www.zephyranywhere.com/system/components

Figure 3.9: The display conditions: (Left) HDTV, (Middle) CPD, (Right) HMD.

3.4.1 Experiment 1: Initial Prototype

For the initial prototype, the goal was to find out which of the current display technologies would be suitable for the AAS environment, the AOP. A comparison was made between a current VR HMD (Oculus Rift CV1), a 270° surround CPD (SimPit Centurion [128]) and a Sony 40" HDTV KLV-40S400A TFT Active Matrix LCD. These display types were chosen because they were a good representation of display types currently available to represent the state-of-the-art in terms of immersion, FoV and display resolution. The three display types are shown in Figure 3.9. Audio was provided in the form of loud consistent engine and rotor sounds, which largely dominate the soundscape in a helicopter.

User Feedback: Summarised feedback from the initial experiment suggested a near-equal preference between the 270° CPD and the HMD. The CPD gave an immersive experience similar to what is experienced in a real cockpit, due to the confined nature of the space, and permitted the physical presence of the pilot, to provide the pilot/co-pilot experience. However, the immersive elements of the CPD could be improved by blacking out all of the supporting structure and ambient lights which reduced the illusion of being inside a real environment. It was also suggested to further improve the presence with immersive features such as vibrotactile feedback to give sensations of turbulence and engine vibration.

The HMD on the other hand was reported to greatly immerse users in the VE, due to its ability to completely block out the real world. However, the 40" HDTV made people feel as if they were looking through the window at the environment, which made them feel more disconnected from the virtual space comparable to the two other display types. The HMD had a better graphical quality than the projection and allowed users to look around the aircraft better with head tracking. This fact made the VE of HMD feel more realistic and provide a greater feeling of Presence with the simulation.

The simulation was experienced as a pre-recorded flight, so it gave the user limited ability to control what was going on other than what they could look at. This gave users a feeling of disconnection with the VE as they could not take a second look at something of interest as they would in a real situation. This prompted the design of the iteration to switch to an interactive multi-user environment, with a focus on communication with crew members. It was decided to continue using the 270° CPD display for the AAS platform, as this gave the most realistic experience of being an AAS. The HMD, while very portable, required many additions to create a similar experience as the projection display. Elements such as rigged 3D avatars, representing the AAS and the AOP pilot, and hand and eye tracking could be added in the virtual world when using an HMD to create a similar co-pilot experience that comes naturally in the CPD.

3.4.2 Experiment 2: Second Iteration

From the user feedback and results of Experiment 1, we made design choices to use the CPD as the main display type for Experiment 2.

The vibrotactile feedback bench seat was also developed for this experiment (Figure 3.10), which aimed at providing a greater level of immersion using a haptic stimulus to simulate the engine vibrations normally experienced in a helicopter.

Figure 3.10: The vibrotactile bench seat and CPD setup.

User Feedback: The vast majority of users rated the disrupted communications as being most stressful of the auditory stimulus. Many said that disruptive radio transmissions were very realistic and a common occurrence in radio communication. This led to an increase in communication frequency, as messages needed to be repeated to ensure the intent of the message had been delivered. It also gave a feeling of anxiety around the whereabouts of the crew, which may have led to further psychological stress. One participant said that the distorted communications distracted them enough to take their mind away from the fire. User feedback suggested that the radio communication built into the simulator should be of high functional fidelity. We, therefore, incorporated actual radio systems to facilitate this feedback in later iterations. The background radio chatter was found to be the second most stressful, while the rotor sound and vibrotactile feedback were rated least stressful. These three factors were found to significantly add to the experience, providing a greater sense of presence as reported by the *General* scale of the IPQ.

Several participants found that the vibrotactile feedback of the vibrating bench-seat was valuable to the user experience, but it could better respond to turbulence or entering a hover. It was also noted that the feet of participants were not directly effected by the vibrations, due to them being placed on the ground. In a helicopter, this sensation would be experienced through the whole body. To facilitate this experience, the vibrotactile bench seat interface was iterated on to extend footrests out that were welded to the frame of the seat shown in Figure 3.11. This created a more rigid structure that allowed vibrations to transfer through the entire body of the user, giving a more lifelike sensory experience of being in a helicopter.

We designed a complex communication interface that could record both conversations between the pilot and AAS, as well as AAS and the flight crew. We integrated the Gold Creek scenario as a part of the design and located the topography where the incident occurred.

3.4.3 Experiment 3: Third Design Iteration

After considering the feedback from the second iteration of testing, the scenario used in Experiment 2 was expanded to a full multi-participant role-play exercise, and integrated into the VRTS. In this scenario, there were three bucketing pilots who were tasked by the AAS trainee to attack the simulated wildfire. Additionally, the ASS and OM provided radio communication stimuli, the same as they would perform in the radio-role play exercise, as described earlier, in the form of radio injects. See Appendix A for the radio injects and the Gold Creek scenario.

Figure 3.11: The vibrotactile helicopter bench seat with footrest extensions.

Since this scenario is already utilized in the existing radio-only exercise of similar format, it made it easier for the trainers to adopt the technology into their pre-existing radio role-play scenario.

User Feedback: It was somewhat difficult for many trainee's to operate the Bucketing Crew stations since they were new to the technology. However, we had already considered this based on previous experiments and provided a staff member to help to train the firefighters on the spot to fly or in some cases to fly for them, while the firefighter operated the radio and practiced the radio protocols. This ended up being quite effective and allowed the operation to run smoothly. There was a desire to make the flying simpler than the flight simulator software allowed so this would be considered for future designs.

Chapter Summary

To summarize this chapter, end-users were specified along with the end-user requirements as defined by the SME in Section 3.1. Section 3.2 provided the technologies used to begin the design process, or step three of the UCD Model. Section 3.3 described the various qualitative and quantitative measures we used for evaluating the VRTS prototype. Lastly, Section 3.4 provided the design iterations which were used for experimentation, showing the changes that were made through the process of iterative design from user studies and feedback. Next, in Chapter 4, the individual experiments that were conducted based on the user requirements are presented in detail to evaluate the system based on each of the fundamental topics identified.

Chapter 4

Empirical Studies

This chapter presents the empirical results and the research methodology used to evaluate our system and answer the research questions presented in Section 1.4.2. Each main section in this chapter presents one study that was conducted, together with a description about the research design process and the results found using quantitative and qualitative measurements. Section 4.1 provides details of the initial study based on *Situation Awareness* SA, Section 4.2 details the second study on *Communication* and Section 4.3 details the third study on *decision making*.

Each of the experiments resulted in peer-review publications: Experiment 1 generated a conference workshop paper [38] and a conference poster regarding evaluating SA in a Virtual Reality Training System (VRTS). Experiment 2 resulted in a conference paper [40] and a journal article [39] in regards to evaluating communication stimuli in a VRTS. Experiment 3 resulted in a conference paper [37] in regards to evaluating decision making in a VRTS.

4.1 Experiment 1: Situation Awareness

SA is a core element for aerial firefighting as was identified in the user-requirements previously discussed in Chapter 2 and Section 3.1. Of the different display technologies that were available for our experiment, we were wondering what display type was more appropriate in training for the AAS role, specifically for the acquisition of SA. In order for our training system to facilitate this, the simulator environment had to be designed to afford adequate visual SA acquisition.

4.1.1 Hypotheses

In this experiment the following hypotheses were made:

H_1 *More-immersive displays are more effective for perceiving elements than less-immersive displays.*

H_2 *More-immersive displays lead to a better comprehension of the situation than less-immersive diplays.*

H_3 *The more immersive a display is, the better the ability for people to predict future outcomes of a given situation is.*

4.1.2 Experiment Objective

This experiment was to explore the validity of the immersive display component of the VRTS and to find out what display type is better for the purpose of the AA role, where gaining SA is of high importance within a VE. SA is also an important aspect of feeling presence in a virtual system, creating an interesting point of research.

1. HDTV

A control condition of a standard FoV display type, a large 40 inch high-definition television (HDTV). The participant could look around the VE using a mouse.

2. CPD

A 270° surround SimPit Centureon CPD, allowing the participant to look around the VE naturally, but not see a virtual image above or below the screen.

3. HMD

An Oculus Rift consumer version VR HMD, allowing the participant to be fully-immersed in the VE and be able to look around on the inside of the VE naturally.

Figure 4.1: The display types used to compare SA and visual immersion.

4.1.3 Experiment Conditions

A comparison study was made between the three conditions shown in Figure 4.1 to assess the quality of SA with the different types of visually immersive interfaces, representing a range of low to high immersive display types currently available.

4.1.4 AAS VRTS First Iteration System Design

The system design of the SA experiment is shown in Figure 4.2.

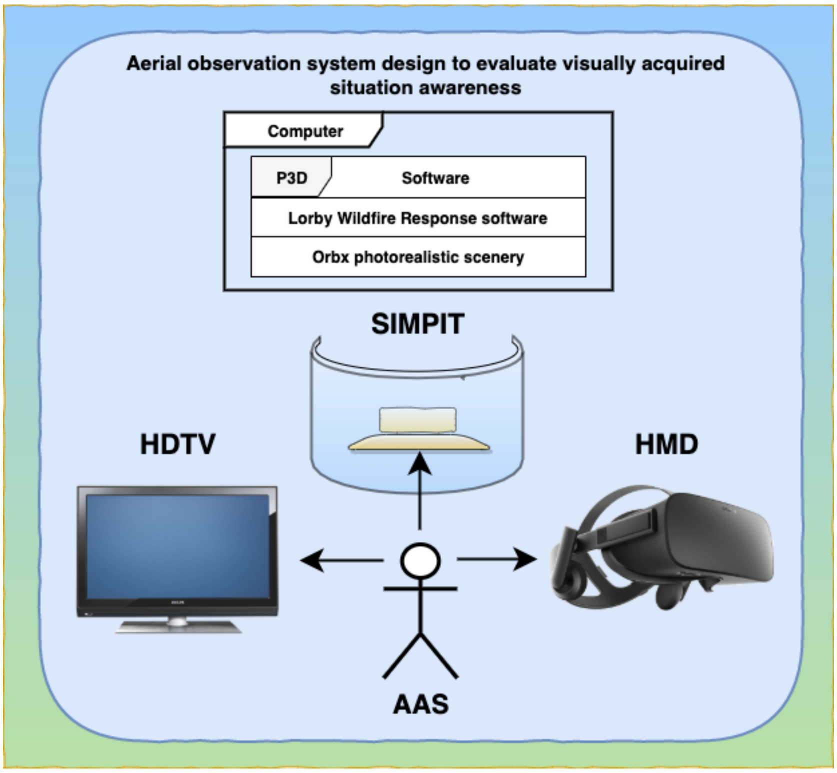

Figure 4.2: The initial prototype SA display evaluation system architecture.

4.1.5 Experiment Design

The experiment aimed to investigate what immersive display type provides a better ability to acquire SA and what provides greater presence to support training objectives in regards to SA. Each of these devices provided a different level of immersion as measured by FoV, which afforded a different sense of presence within the VE. Questions relating to aerial firefighting in regards to SA were established and are presented below in Section 4.1.7.1. Standardised questionnaires for presence and simulator sickness were used to evaluate the system in this initial iteration of the VRTS. A copy of this questionnaire is supplied in Appendix A.2.2. The experiment conditions were counterbalanced using a 3 x 3 Latin square ordering. This was done to remove learning biases between the conditions as well as bias from fatigue. The Latin square used for this experiment is provided in Appendix A.2.1, which balances the three display types HDTV, CPD & HMD) and three environmental conditions (Port Hills, Onamalutu & Aoraki), detailed in Section 4.1.7.2.

4.1.5.1 Experiment Task

A typical task performed by the AAS is an aerial observation to gain early SA after a report of a fire has been made, usually by the public to the emergency services. In this experiment, the aerial observation task was replicated, using a pre-recorded flight re-played for each participant. Each participant received exactly the same virtual exposure in each condition. From take off, the virtual AOP helicopter would fly to the fireground from a fixed location and arrive at the fireground at approximately three minutes into the simulated flight, entering a circuit around the fire. At approximately five minutes, the system would freeze mid flight, prompting the user to exit the simulation and begin filling out questionnaires in regards to SA, presence and simulator sickness.

4.1.6 Procedure

The following process was carried out from the moment the participant arrived:

1. Welcome participant, provide information about the study and have the participant complete the consent form.

2. Participant completes demographics and pre-experiment questionnaire.

3. Give participant briefing (Section 4.1.6.2) for the first condition.

4. Participant placed in first condition.
5. Perform first freeze probe questionnaire.
6. Participant placed in second condition.
7. Perform second freeze probe questionnaire.
8. Participant placed in third condition.
9. Perform third freeze probe questionnaire.
10. Participant completes post-experiment questionnaire.
11. Thank the participant for their time and reward them with a $10 gift voucher.

4.1.6.1 Order of Freeze Probe Questions

In an effort to maintain the participant's ability to actively recall elements, it was necessary to consider the order in which the questionnaires were presented. The freeze probe questionnaires were presented after each of the following experiment conditions:

1. L1 SA Questions
2. Map Task
3. L2 SA Questions
4. L3 SA Questions
5. Igroup Presence Questionnaire
6. Simulator Sickness Questionnaire

4.1.6.2 Briefing

The briefing (shown in Figure 4.3) was given in paper format to each participant prior to starting each of the three display conditions (HDTV, HMD and CPD). The briefing indicated what the participant was expected to remember during the exposure period.

We have recieved notification of a fire in this area!

The following factors will influence the outcome of the firefighting operation:

- **Power lines (risk of wirestrike to helicopters)**
- **Buildings and Houses**
- **Water supply points**
- **Terrain types, i.e. inclines like hills/mountainous terrain/flat land**
- **The Weather.**
- **Different types of fuels such as:**
    - **Forestry Sections (Radiata Pine)**
    - **Other tree types**
    - **Dry grass**

Fire spreads rapidliy through dry grass. Pine trees are highly volatile due to the flammible sap..

Inclines in the landscape also enable a fire to spread more rapidly due to the effect of heat rising.

Powerlines and other cables that are difficult to spot can be disasterous for helicopters.

You will be asked about:

1. **What elements you saw during the flight.**
2. **What the current state of these factors are.**
3. **What the future state of these factors are based on expected fire growth.**

Please prepare yourself for your flight and let the experimentor know when you are ready...

Figure 4.3: Briefing paper given to participants prior to each condition

4.1.7 Measurements

This section provides the different measurements used in order to test our hypotheses. Comparisons were made from datasets generated by questionnaires completed by participants from each of the three display types (HMD, HDTV and CPD) in regards to the three levels of SA (described below). Additionally, data was captured on perceived presence and simulator sickness.

4.1.7.1 Situation Awareness Questions

Endsley [51] stipulates that in order to attain complete or total SA, three levels of SA must be met: *(L1SA) Perception of the elements, (L2SA) Comprehension of the situation and (L3SA) Prediction of future status.* To evaluate this, a set of questions regarding SA were created and validated by AA SMEs as follows:

Level 1: (L1SA) Perception of the elements.

- **Q1** *Were there any buildings nearby?*
- **Q2** *Can you describe any elements you saw mentioned in the briefing?*
- **Q3** *Did you see any power lines in the near vicinity of the fire? Please describe.*
- **Q4** *Did you see any people in the area?*
- **Q5** *Was the fire in a gully, on a hill or on flat land?*

Level 2: (L2SA) Comprehension of the situation.

- **Q1** *How big is the fire currently?*
- **Q2** *Out of the elements previously described, what do you think the fire poses an immediate threat to?*

Q3 *How difficult do you think it will be for ground crews and vehicles to access the fire?*

Level 3: (L3SA) Prediction of future status.

Q1 *If this fire continued for several days, how do you expect this fire to evolve?*

Q2 *What additional areas that are populated would need to be evacuated, if any?*

4.1.7.2 Map Task

After the *(L1SA)* questions, a map task was provided to determine two items: the participant's awareness of the location of hazards and other assets potentially threatened by the fire, as well as their ability to accurately judge the location of the fire. The map-based task was evaluated with an accuracy rating out of 10 in regards to how many of the elements that were present in the VE were reported by the participant. Each map had 10 elements such as power lines, heavy machinery, structures or people. The ability to accurately locate the fire was determined by measuring the distance from the actual fire location and the location reported by participants. A score of 10 was given if the distance was less than one centimeter. For each centimeter from the actual fire location, the total score was reduced by one point. Anything over 10 centimeters was given a score of zero. These scores contributed to the L1SA results. The L2SA and L3SA set of questions are provided directly after the map task.

4.1.7.3 Air Observation Maps

The paper maps shown in Figure 4.4, Figure 4.5 and Figure 4.6 were provided on A3 paper to the participants to locate elements in the simulation. The maps were created by elevating the simulation to a height of approximately 25,000m and taking a screenshot, aligned to the North. This was done to ensure the same geographical features existed on the map, as what was experienced in the VE.

Figure 4.4: Map of Aoraki/Mount Cook.

Figure 4.5: Map of Onamalutu, Marlborough.

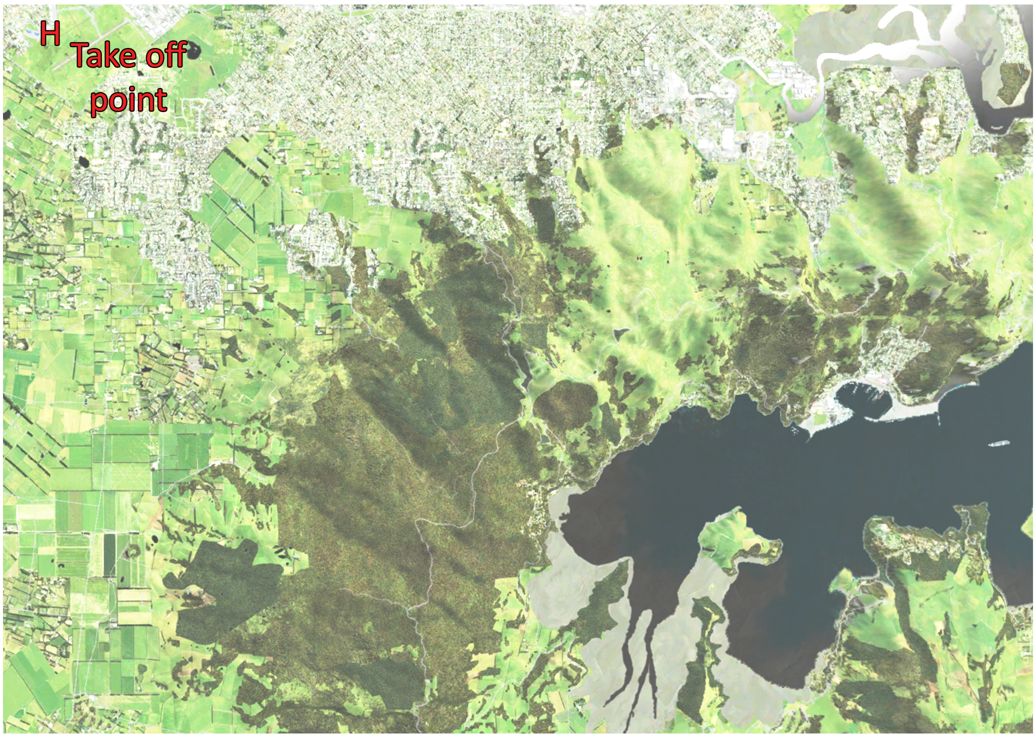

Figure 4.6: Map of Port Hills, Ōtautahi/Christchurch.

4.1.7.4 Subjective Questionnaires

To determine the level of Presence for each display type, subjective ratings following the IPQ guidelines were assessed for each of the display type experiences. Similarly, to determine what level of simulator sickness each of the display types provided, the SSQ was utilized. Each of these questionnaires was executed using the SAGAT, using a freeze probe after approximately five minutes of exposure time in each condition. At the end of the last condition, a post experiment questionnaire was given to participants regarding the user experience in regards to each of the displays and which display was preferred.

4.1.8 Results

We compared the three SA levels L1SA, L2SA and L3SA between the different display types. We also looked for differences in Presence and simulator sickness. In all statistical analyses, N = 36. Friedman and Wilcoxon Signed-Rank Tests were utilized in all comparisons to find significance.

4.1.8.1 Participants

In this experiment, a partial convenience sample was used in addition to end-users for the participant pool. This was decided due to the early prototype stage and based on visual search and not the full set of AAS skills. A total of 36 participants were recruited, with the following occupations: thirteen university students, nine software engineers, six FENZ personnel and eight participants who selected "Other". There were a total of 25 male and 11 female participants, with an average age of 33 years. 72.2% had experienced HMD-based VR and 58% had experienced a vehicle simulator.

4.1.8.2 Level 1 SA: Perception of the Elements

These results are presented in Figure 4.7. Significance was discovered in L1SA, $\chi2(2) = 13.504$, $p = 0.010$. HMD scores ($M = 7.67$, $SD = 1.757$) were significantly greater than the HDTV ($M = 6.53$, $SD = 2.286$) results ($z = -2.416$, $p = 0.016$). The CPD scores ($M = 7.75$, $SD = 1.857$) were also significantly greater than the HDTV ($M = 6.53$, $SD = 2.286$) scores ($Z = -3.299$, $p = 0.001$). No significance was found between the immersive display types HMD and CPD.

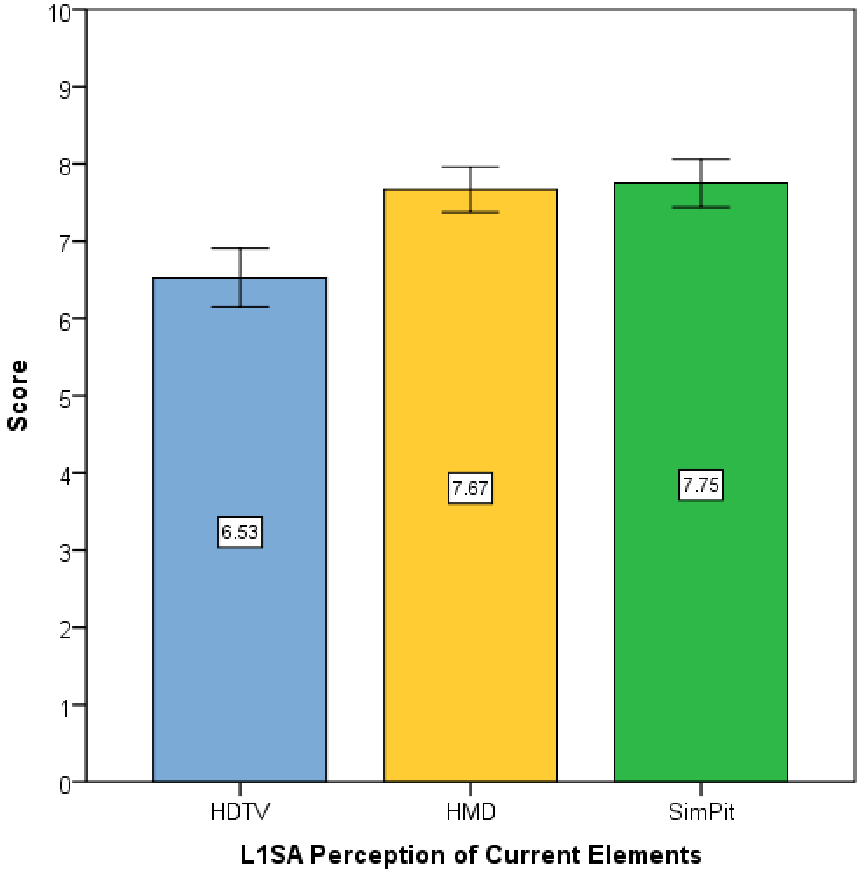

Figure 4.7: Perception of element scores (higher scores are better).

4.1.8.3 Level 2 SA: Comprehension of the Situation

These results are presented in Figure 4.8. Significance was discovered in L2SA, $\chi2(2) = 10.067$, $p = 0.007$. HMD ($M = 6.14$, $SD = 2.153$) scores were significantly greater than the HDTV ($M = 5.06$, $SD = 2.083$) scores ($z = -2.246$, $p = 0.025$). The CPD scores ($M = 6.47$, $SD = 2.077$) were also significantly greater than the HDTV ($M = 5.06$, $SD = 2.083$) scores ($Z = -3.420$, $p = 0.001$). No significant differences were discovered between the two immersive display types HMD and the CPD.

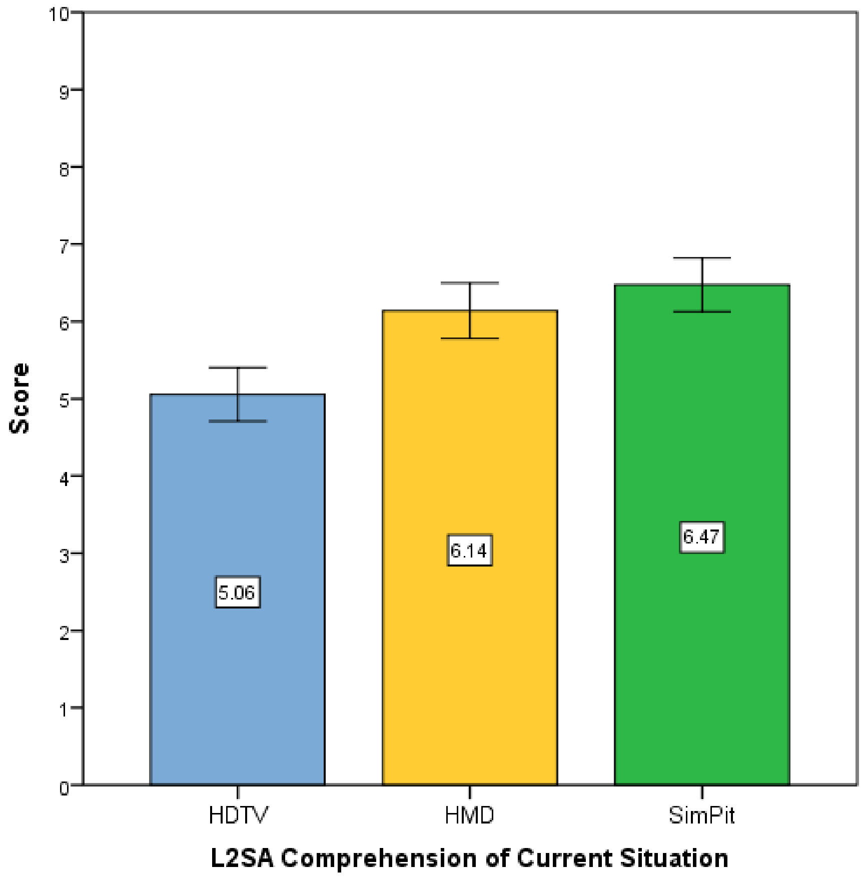

Figure 4.8: Comprehension of the situation scores (higher scores are better).

4.1.8.4 Level 3 SA: Prediction of Future Status

These results are presented in Figure 4.9. Significance was discovered in L3SA, $\chi2(2) = 6.104, p = 0.047$. The HMD ($M = 5.58, SD = 2.802$) scores were significantly greater than the HDTV ($M = 4.25, SD = 2.310$) scores ($z = -2.525, p = 0.012$). The CPD ($M = 5.30, SD = 2.993$) scores were also significantly greater than the HDTV ($M = 4.25, SD = 2.310$) scores ($Z = -2.153, p = 0.031$). No significant differences were found between the HMD and CPD.

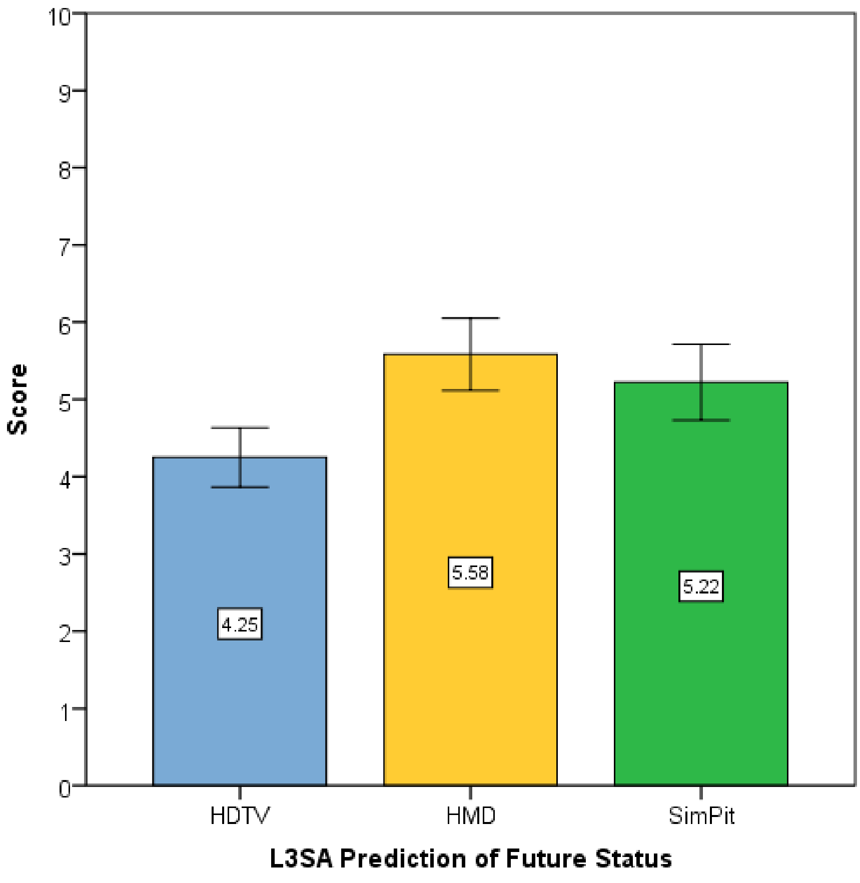

Figure 4.9: Prediction of future status scores (higher scores are better).

4.1.8.5 Presence

Significance was discovered, $\chi2(2) = 44.57$, $(p < 0.001)$, for Presence measures. HMD scores $(M = 3.99, SD = 0.777)$ were significantly higher than HDTV scores $(M = 2.22, SD = 1.027)$, $(z = -4.969, p<0.001)$. Also, the CPD $(M = 3.55, SD = 0.945)$ scores were significantly higher than the HDTV $(M = 2.22, SD = 1.027)$ scores $(Z = -4.859, p<0.001)$. Lastly, the HMD $(M = 3.99, SD = 0.777)$ was statistically significantly higher than the CPD $(M = 3.55, SD = 0.945)$ scores $(Z = -2.659, p = 0.008)$.

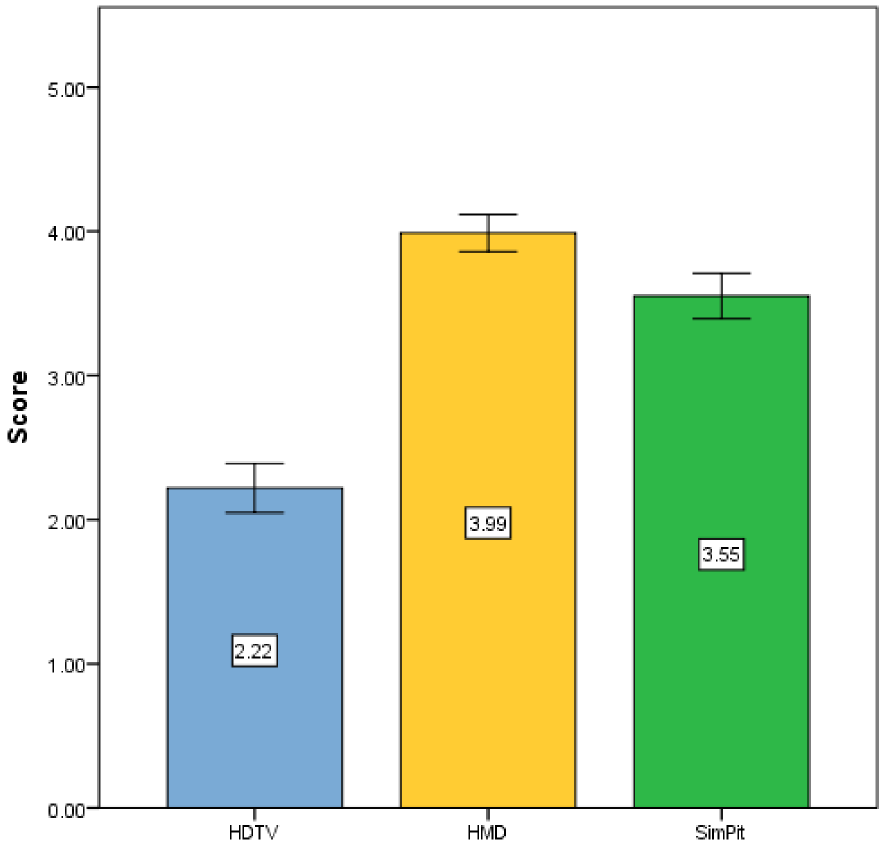

Figure 4.10: Igroup Presence Questionnaire results for each display type.

4.1.8.6 Simulator Sickness

Five outliers were removed using SPSS stem and leaf outlier detection, where these scores deviated by a factor of 1.5 times the inter-quartile range. Significance was discovered, $\chi2(2) = 15.75, p<0.001$. Significance was found between the HDTV ($M = 3.06, SD = 5.413$) and HMD ($M = 15.07, SD = 16.976$) results ($z = -3.595, p = 0.012$), as well as between the HMD ($M = 15.07, SD = 16.976$) and the CPD ($M = 5.61, SD = 9.401$) results ($Z = -3.10, p = 0.002$). No significant differences were found between the HDTV and CPD.

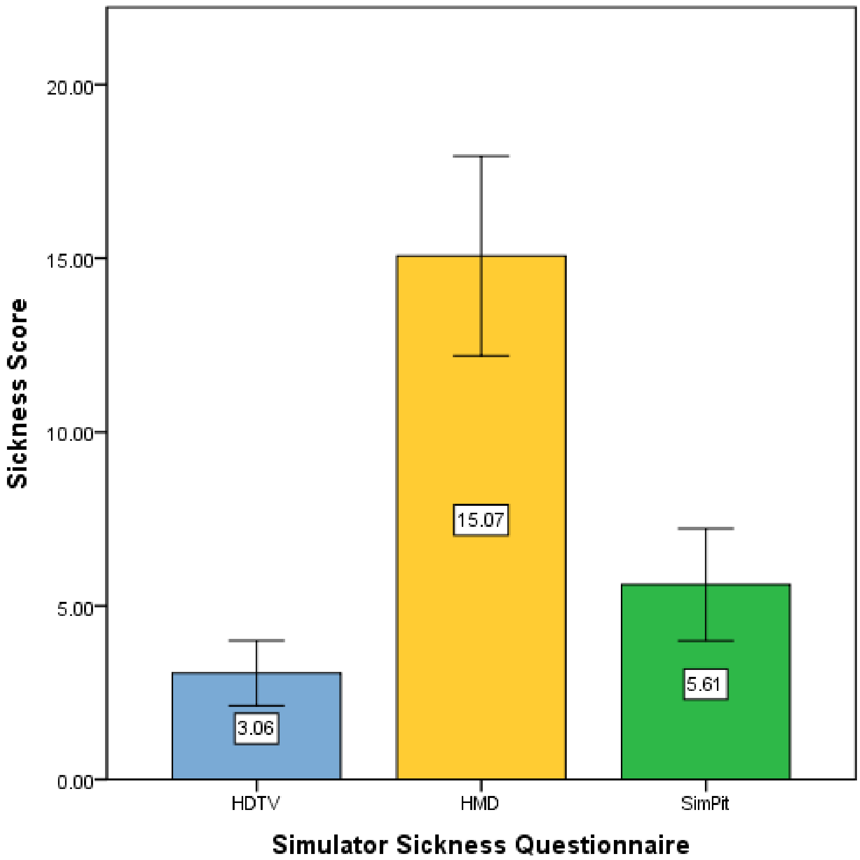

Figure 4.11: Simulator sickness results by display type (lower scores are better).

4.1.9 Display Preference

Participants ranked their preference for each display for the task. A significant difference $\chi2(2) = 20.1, p<0.001$ was discovered by post-hoc analysis, which revealed a significant difference for two pairs: HMD and HDTV ($Z = -4.159, p<0.001$), CPD and HDTV ($Z = -3.540, p<0.001$). The difference between the HMD and the CPD was not significant ($p = 0.298$). Participants preferred the HMD (Mean Rank: 1.6), followed by the CPD (Mean Rank: 1.9), and then the HDTV (Mean Rank: 2.6)

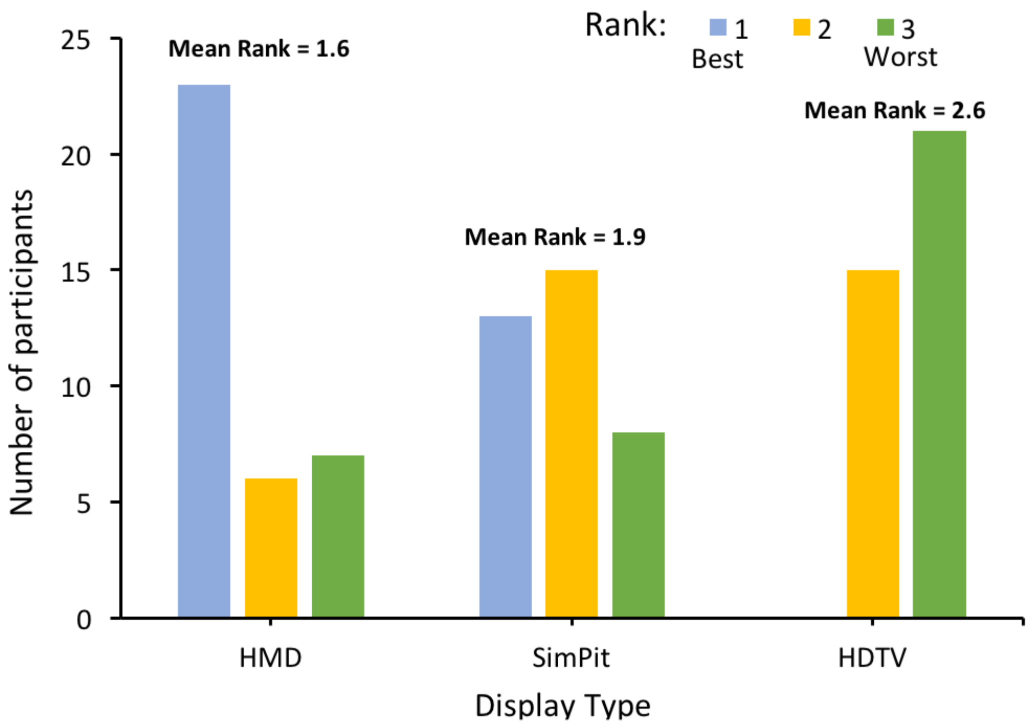

Figure 4.12: Display preferences reported by participants.

User experience feedback It was noted that the length of the questionnaires was fairly long and tended to disrupt the flow of being immersed in the task. This was considered to be a major limitation in the experiment design. For example, a considerable length of time had passed by the time participants got to the IPQ or SSQ questionnaires which might have made these questionnaires suffer from a bias. Future experiments were subsequently designed to keep the question time to a minimum and incorporate objective measurements such as physiology sensors to detect stress. Participants reported that the HMD gave them the sensation of being on the inside of a helicopter, as they could look around the cockpit and could look around the pillars to get a better view. This sensation was not present in the CPD, where participants had to wait until the aircraft had moved to be able to see objects behind the pillars. This led to many participants under-rating the CPD. The CPD would need to have more realistic helicopter cockpit elements to improve the level of presence that the users experience with the system.

4.1.10 Discussion

From the results presented, it can be seen that the ability to locate the fire on the map task was unaffected by the display type. The fire was considered to be the primary element during the visual scanning task, so participants focused almost solely on it. Secondary targets, such as power lines, vehicles and water dipping locations, were more difficult to perceive in the low FoV display, as shown by the *L1SA* results presented in Figure 4.7, supporting $\mathbf{H}_1$. From these results, we can see that there is a statistically significant difference for both immersive display types, the HMD and the CPD, compared to the HDTV. For the *L2SA Comprehension of Current Situation results*, we see statistically significant differences again for both immersive display types compared with the HDTV (Figure 4.8), supporting $\mathbf{H}_2$. This could be because the presence associated with the immersive displays enables people to feel more situated in the learning task, or could be a carryover effect from positive L1SA results. The same applies for *L3SA Prediction of Future Status*, as the immersive displays afforded greater presence, enabling better judgment of what would occur in the future. We can see that there is a significant improvement for each of the three levels of SA for both immersive interface displays (HMD and CPD) over the non-immersive HDTV display, supporting $\mathbf{H}_3$. The results support the hypotheses that the immersive displays are better at providing total SA for this particular AAS task. From the user experience feedback, it was shown that there were restrictions to the visual capability to the CPD, which may explain the difference in reported presence scores. Although many users preferred the HMD and it created a greater level of presence as reported by IPQ scores. The CPD was decided to be used for the next experiment, with the addition of vibrotactile feedback, to improve the immersion of the system.

4.2 Experiment 2: Disruptive Communications

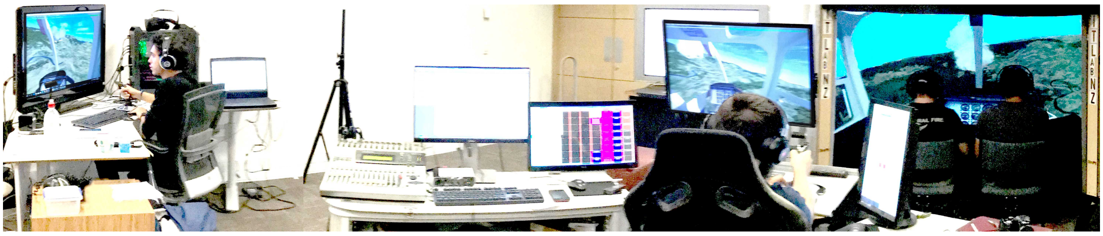

Figure 4.13: The disruptive communication study configuration: (Left) Research assistant as bucket one, (Middle) Researcher station, (Right) AOP simulator with Participant (as AAS) on left and research assistant (as AOP pilot).

The effect of radio disruptions on the stress levels of trainees is an important consideration, since the tool is used heavily in both aviation and in the firefighting domains. In this experiment, we hypothesize that novice users feel more stress than (i.e., are not able to handle stressful situations as easily) a highly trained firefighter, the target user group of AAS. A natural human response would be to show signs of heightened nervousness or physiological response, such as changes in HRV or Breathing Rate (BR). However, we would expect that an expert would be less susceptible to the conditions reflected in their physiology, as they would be confident in their ability to perform, at least up until the point where the task becomes overwhelmingly difficult. This would be reflected by their skill level or capacity to handle the situation in a typical complex and noisy aircraft environment. When background radio chatter is present, a cocktail party effect [26] may take place, where effects of *helmet-fire* cause confusion or selective hearing. Experienced communicators can effectively manage multiple conversations simultaneously, ignoring conversations that do not pertain to them and keeping an ear on the other radio chatter. Additional miscommunication errors caused by equipment failure can cause further disruption.

4.2.1 Hypotheses

Considering the effect and dependency of communications on the situated task, we looked at the common issues experienced with typical radio communication systems. We identified critical factors such as background radio chatter and signal disruptions as experimental conditions. A repeated action, a Push-to-Talk (PTT) foot-switch, is used to enable radio communication. Based on this, the hypotheses for the experiment were as follows:

H_1 *Participants can effectively communicate and respond to human helicopter pilots, AI fixed-wing pilots and the operations manager, using the simulated emergency radio communication system.*

- **$H_{1.1}$** *Communication effectiveness for participants with radio experience is more efficient than participants without.*

H_2 *Participant's sense of Presence increases as additional radio stimulus in the VE is added as measured with the IPQ.*

H_3 *Added stressors in the system, such as background chatter and disrupted communications, have a noticeable effect on physiological stress.*

- **$H_{3.1}$** *There is an observable decrease in HRV.*
- **$H_{3.2}$** *There is an observable increase in BR.*

H_4 *The system will elicit an increase in perceived stress over time, measured by relevant sub-scales (energetic arousal, tense arousal, anger / frustration and concentration) of the DSSQ.*

4.2.2 Experiment Objective

The aim of this experiment was to evaluate how compounded communication stressors has an effect on the physiological stress and performance ability of AAS. This experiment explores elements of radio communication that creates occupationally relevant stress for AAS.

4.2.3 Experiment Conditions

To understand the effects of communication disruption on the physiological stress and communication ability in AAS, we designed an experiment that involved the following three conditions:

(C_1) Radio, helicopter noise and vibrotactile feedback.

(C_2) Condition C_1 with background radio chatter extracted from the Gold Creek fire incident.

(C_3) Condition C_2 with the inclusion of broken transmissions/signal failure.

4.2.4 Experiment Design

This experiment was designed to elicit stress from the user to emulate helmet-fire and other communication related stress. All participants experienced the same order of conditions. This was done to ensure all participants received the same exposure without breaking the flow of the experiment and creating complexity in the data.

Communication and physiological data was captured in real time to show these effects, in combination with pre and post experiment questionnaires on stress and presence.

4.2.5 AAS VRTS Second Iteration System Diagram

The system design for the communication experiment is shown in Figure 4.14.

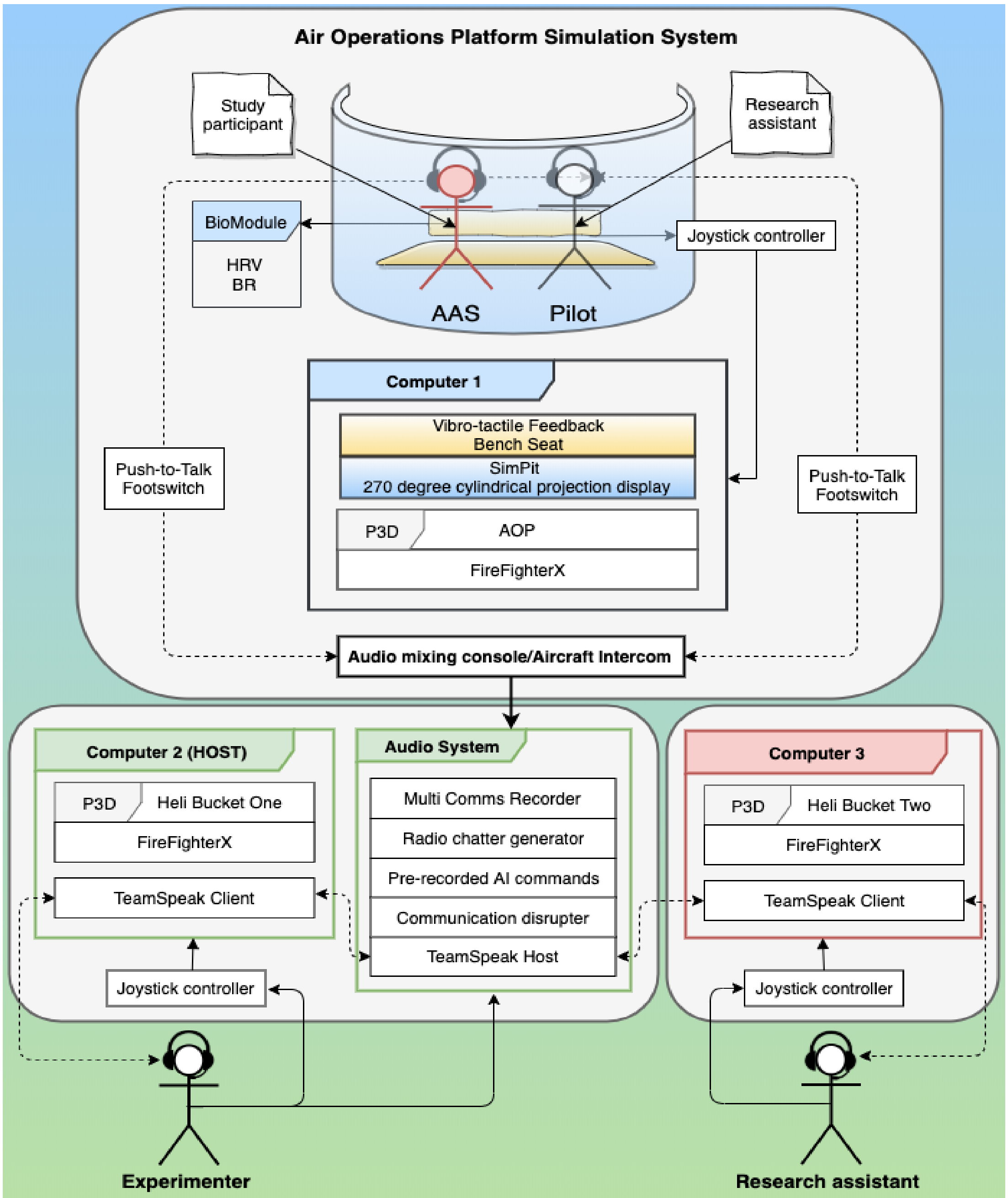

Figure 4.14: Disruptive communications experiment system diagram.

4.2.5.1 Experiment Task

Participants were asked to perform radio communication tasks which required them to utilize the radio hardware to communicate with all parties in the simulation; the AOP pilot, the two bucketing pilots, the AI fixed-wing support aircraft and the operations manager.

The PTT foot-switch was provided to communicate with those outside of the AOP, which is normal in such a helicopter radio system. The PTT foot-switch activity was logged to allow us to track the frequency of outgoing communication behavior. To talk to the AOP pilot, participants could openly communicate using the on-board intercom, as well as use hand gestures to indicate their intention. All radio communication was recorded for further analysis.

4.2.6 Procedure

The following process was carried out from the moment the participant arrived:

1. Welcome participant, provide information about the study and have the participant complete the consent form.

2. Activate and fit Zephyr Biomodule™ to participant to obtain a stable HRV (approx. 5 min for 100% confidence).

3. The participant now completes demographics and pre-experiment questionnaires, while waiting for the HRV sensor to gain 100% confidence (approx. five minutes).

4. Participant performs breathing exercise for four minutes, when HRV is at 100% confidence to obtain the relaxed state HRV.

5. Participant now sits in the virtual AOP co-pilot seat, ready to begin the training exercise.

6. Perform communication sound checks, to ensure everyone can talk and for the participant to become familiar with the PTT foot-switch system.
7. Experiment scenario begins ($\mathbf{C}_1$), all helicopters take off and fly to fire ground.
8. 10 minutes in, introduce $\mathbf{C}_2$.
9. 15 minutes in, send in fixed-wing AI Aircraft 1.
10. 20 minutes in, introduce $\mathbf{C}_3$.
11. 25 minutes in, send in fixed-wing AI Aircraft 2.
12. 28 minutes, low fuel warning; return to base.
13. 30 min in, landing at base.
14. Perform post experiment breathing exercise.
15. Participant completes post experiment questionnaire.
16. Remove Zephyr Biomodule™ from participant.
17. Thank participant for their time and reward them with a $10 gift voucher.

4.2.7 Measurements

In this subsection, details about the measurements used to evaluate the VRTS are provided. Subjective measurements were used to profile presence within the system as well as operator stress state.

4.2.7.1 Validated Questionnaires on Presence and Stress

Existing questionnaires were used for detecting subjective operator state for Presence and stress in a VR system. The IPQ is a seven point scale used to detect Presence in a VE [122]. The DSSQ [35; 94] was used to find subjective stress within the system.

4.2.7.2 Physiological Data

HRV and BR were measured. A lower HRV value or shorter inter-beat interval means the heart is beating more rapidly, indicating stress. The higher the BR, the more stress the user is experiencing. We obtained this data before, during and after the stimulus exposure. To compare and interpret this data, we took the average of the HRV from each participant during the experiment. We took an average of 100 samples that were recorded at a rate of 1 sample per second (1Hz) after the introduction of each stimuli and then subtracted this from the peak HRV value reached during the initial breathing exercise (BE1). This was done due to individual physiological differences, so we consider this method unbiased towards people who have a generally high HRV.

We also compared the previous four-minute breathing exercise HRV versus the same post-breathing exercise (BE2) after the simulation experience to look for stress recovery. Stress recovery indicating whether participants were in fact subjected to stress due to a positive change in HRV from the initial breathing exercise (BE1). A positive response in this situation (greater than zero) indicates a better ability to recover from stress, implying the participant is better at handling stressful situations.

4.2.8 Results

This section provides the results of the study on communication disruption.

4.2.8.1 Participants

A total of 25 participants with an average age of 39 years were involved in the study. Two females and 23 males. There were eight AAS, six firefighters without AAS experience but with radio experience, and eleven civilian participants, two of which had between six and ten years radio experience. Of the non-AAS group, four participants had between one to five years firefighting experience, with two having more than sixteen years experience. Of the AAS group, four have over sixteen years firefighter experience, three of which had more than seven years in AA. The remaining five AASs had been involved in AA for one to two years. Four out of the seven AAS had more than sixteen years of radio communication experience, one reporting between eleven and fifteen years radio experience and one reporting 5 years radio experience, who was the least experienced AAS trainee.

Table 4.1: The average number of foot-switch presses during experimental phases between participants with and without radio experience.

Condition	No radio exp.	Radio exp.
(**C**$_1$) No disruption	27.50 ± 8.361	21.77 ± 5.747
(**C**$_2$) Background chatter only	27.83 ± 12.782	24.54 ± 5.142
(**C**$_3$) Chatter and signal failure	28.83 ± 11.071	22.08 ± 11.124

4.2.8.2 PTT Footswitch operation

Systematic errors occurred during the experiment, which resulted in some of the foot-switch presses failing to be recorded for six of the participants (two AAS and four civilian). The remaining sample consisted of thirteen firefighter participants (six AAS trainees, six non-AAS) and seven civilian participants without radio experience. Looking at the number of foot-switch presses during the periods of (**C**$_1$) no communication disruption, (**C**$_2$) disruption through background chatter and (**C**$_3$) disruption through background chatter plus periodic signal failure, we observed participants with radio experience managed to more effectively communicate during the experiment (Table 4.1). Needing fewer foot-switch presses on average suggests the ability to issue instructions more efficiently, making overall communication more effective without cluttering the radio channel. However a t-test revealed no significance for existing radio experience in all three conditions: (C$_1$) $p = 0.171$, (C$_2$) $p = 0.565$ and (C$_3$) $p = 0.245$. However, when comparing AAS and non-AAS firefighters revealed a significant difference in the final condition (C$_3$) where the AAS ($M = 15.83, SD = 6.853$) would use the PTT fewer times than non-AAS ($M = 29.33, SD = 11.518$) $p<0.05$, but not for (C$_1$) $p = 0.310$ or (C$_2$) $p = 0.426$ for the mean number of PTT footswitch presses.

4.2.8.3 Presence

A One Sample t-test was used to evaluate the results of the IPQ survey, presented in Figure 4.15. Generally, participants felt a strong sense of Presence in the VE. The combined score of the IPQ ($M = 4.5, SD = 0.70$) was significantly above the neutral midpoint (4.0) of the seven-point scale $t(24) = 3.549, p = 0.002$. The mean *General Presence* score $M = 5.72, SD = 1.021$ was significantly higher than the neutral midpoint, $t(24) = 8.420, p<0.01$. The *Spatial Presence* mean ($M = 5.31, SD = 0.864$) was significantly greater than the neutral midpoint of 4.0, $t(24) = 7.590, p<0.01$. The *Involvement* mean was ($M = 4.60, SD = 1.53$) and was not found to be significantly higher than the midpoint $(24) = 1.956, p = 0.062$. *Experienced Realism* mean ($M = 3.10, SD = 0.510$) was significantly lower than the neutral midpoint $t(24) = -8.818, p<0.01$.

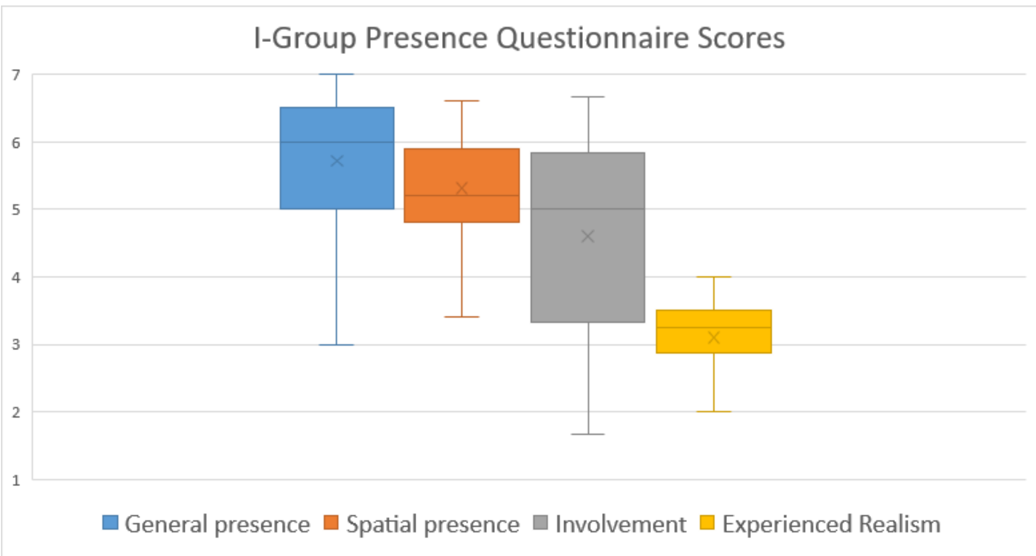

Figure 4.15: IPQ Results from Experiment 2.

4.2.8.4 Physiology Sensor Results

The following results are in regards to the objective data gathered from the physiological sensor from each participant that had been fitted for the duration of the experiment.

Heart-Rate Variability A repeated measures GLM data analysis was conducted and found the average HRV from the baseline were significantly different ($F(2, 48) = 19.10, p<0.001$). The second phase ($M = -26.31, SD = 18.81, p<0.001$) and the third phase ($M = -27.22, SD = 20.77, p = 0.001$) were significantly lower than the first phase ($M = -9.34, SD = 19.56$). The difference between the second and the third phase was not significant ($p = 0.941$). We also found a highly significant within-subject linear contrast for the first three phases, indicating that the HRV decreased with the progress of the phases. Since a lower HRV is correlated with higher stress, we can see that participants felt more stressed as the complexity increased (and as time went on).

Breathing Rate A repeated measures GLM data analysis was conducted and found that the average BR differences were significantly different ($F(2, 48) = 9.84), p<0.001$). The second ($M = 8.68, SD = 5.42, p<0.003$) and third ($M = 8.56, SD = 5.35, p = .002$) were significantly lower than the first condition ($M = 10.78, SD = 4.59$). The difference between the second and the third conditions (Figure 4.17) was not significant ($p = 0.995$). There was a highly significant within-subject linear contrast for the three phases, which indicates that the BR decreased with the phases. This suggests that participants reduced their respiratory frequency with the progress of the experiment and interestingly reveals an inverse relationship between increasing the complexity of the radio communications and BR.

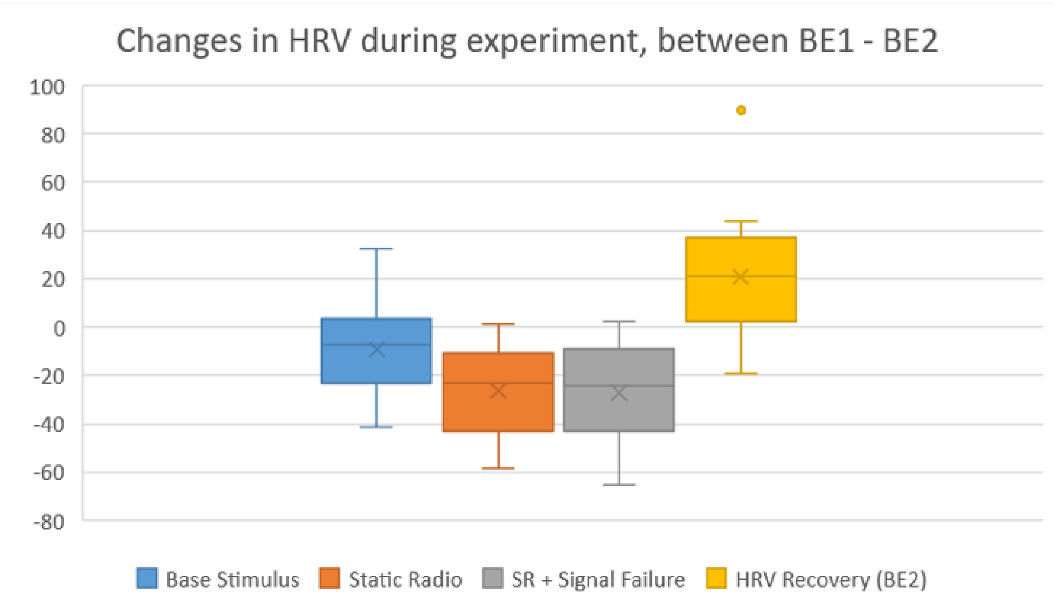

Figure 4.16: Average HRV means after each condition and HRV Recovery phase (BE2).

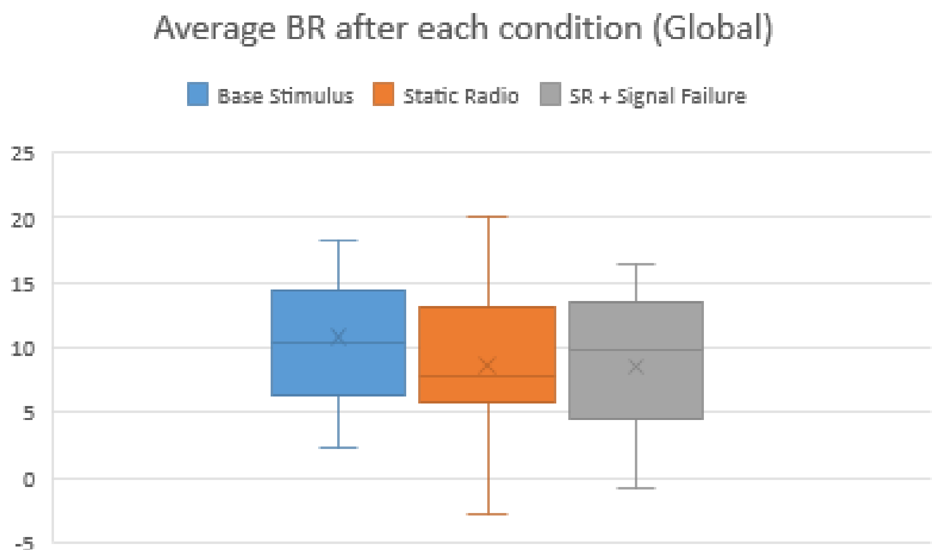

Figure 4.17: BR means after each condition for all participants.

4.2.8.5 Self-reported Stress DSSQ Questionnaire

Participant self-reported ratings of their experience during the use of the system were compared with their stress state before the intervention on relevant sub-scales of the DSSQ (Table 4.2). The repeated measures GLM statistical analysis showed that *Energetic Arousal* during exposure was significantly higher ($F(1,24) = 18.805, p{<}0.001$) and *Concentration* ($F(1,24) = 18.498, p{<}0.001$). *Tense Arousal* ($p = 0.222$) and *Anger/Frustration* ($p = 0.571$) were not significant.

Table 4.2: Scores for DSSQ, *indicates statistical significance

Sub-scale	Before	After
∗Energetic arousal	23.60 ± 3.20	26.48 ± 3.16
Tense arousal	14.60 ± 4.94	15.88 ± 4.94
Anger/frustration	18.44 ± 2.12	18.68 ± 2.38
∗Concentration	17.24 ± 3.50	19.12 ± 3.00

User experience feedback In regards to the user experience of the stressors, 72% of participants (18/25) ranked C_3 as the most stressful. The majority reported that it made them feel like they were not in control of the situation. One participant said,"When the communication became difficult to hear I did not feel in control of the incident."

In this condition, participants stated that they had to rely on other pilots to pass along messages, clarify messages multiple times and were uncertain concerning the instructions given and status of them being received. Two participants with previous radio experience described the distorted communications as not stressful at all, as this is standard for anyone having radio experience. The background chatter was stated to be quiet enough to be tuned out by several of the participants who possessed radio experience. The following feedback from participant responses to open ended question about the stressors included"With distorted communications and background radio chatter, you're fearing to miss teammates communications and wing craft interventions". "The engine sound and the vibrations make the simulation much more immersive", "It mean(t) I had to ask them (the pilots) to repeat what they were saying and took my mind off the fire and made it hard to make choices. Overall, participants thoroughly enjoyed using the system, with AAS trainees enthusiastic about adding this to their training regime. Others reported the background radio chatter to be tolerable and easy to dismiss in the simulation, including the following participant responses, "The background radio chatter was hard because you were trying to listen to the helicopters but other people were talking." "Background radio chatter was fine as long as it didn't interfere with the communication" and "I ignored most of radio noise/chatter as ambient sound.

4.2.9 Discussion

All 25 participants communicated with human and AI pilots using the foot-switch communication interface. All participants effectively communicated a tactical vantage point to the AOP pilot. Our system was proven to be usable by trainees of all experience levels as they all completed the task effectively, producing the number of foot-switch presses for each user group as shown in Table 4.1. From this information, we conclude that $\mathbf{H}_1$ is supported, as all participants successfully grasped the concept of using the foot-switch to communicate outside of the AOP, while being able to communicate effectively locally within the AOP.

Regarding $\mathbf{H}_{1.1}$, the limited amount of available data reduces statistical analysis strength, however we collected qualitative information. The number of foot-switch presses was higher for the participants without radio experience compared with those who had radio experiences as shown in Table 4.1. However, because the data was not significant, our $\mathbf{H}_{1.1}$ sub-hypothesis is not supported by the data. Although the final condition did provide significance between AAS personnel and general firefighter personnel, this suggests that the more experienced firefighters can manage complex radio conditions involving disrupted communications better than the less experienced firefighters. Further research needs to be conducted with a larger pool of participants to draw any solid conclusions about $\mathbf{H}_{1.1}$.

Considering $\mathbf{H}_2$, participants provided a significantly different score in both, general Presence and spatial presence within our system, supporting this hypothesis. Involvement was not significantly different from the observed midpoint score. The experienced realism was significantly lower than the observable midpoint score.

As outlined by Schubert et al. [122], the concepts of involvement and spatial presence are distinct and independent during measurement. The significantly high spatial presence measures could be explained by the high fidelity of the simulated cockpit during the experiment. Using the same motions in the VE as in the actual task has an influence on the experience of spatial presence, while not influencing the experienced realism and involvement to the same degree [114]. It could be argued that the heavy focus on audio stimuli and communication took away some attention from the VE during the experiment, which could have resulted in the lower involvement scores. This could also explain the low experienced realism scores. Nevertheless, the general presence scores indicate that participants did feel *as if they were there*, which was backed up by many participants, especially AA personnel remarking on the realism. A heavier load on the spatial presence scores was found when obtaining the score for general presence, which comprises of all three factors. With the general presence score being significantly higher, we conclude that $\mathbf{H}_2$ is at least partially supported.

The reduction in HRV from C_1 to C_3 suggests that the stress level of participants increased with the addition of stressors (Figure 4.16). We can see that the overall recovery rate of HRV from the experiment is increasing, which indicates that the experiment induced stress (HRV Recovery BE2, Figure 4.16). It was observed that the HRV during C_2 (background radio chatter) and C_3 (background radio chatter plus distorted communications) are significantly lower than condition one. However, they both show differences between the initial breathing exercise and the base stimulus, partially supporting our sub-hypothesis $\mathbf{H}_{3.1}$. We were expecting to see a significant drop in HRV considering the effects were layered, from C_2 to C_3, which was still true when looking within the individual groups of expertise. However, since no significant reduction in HRV occurred overall, $\mathbf{H}_{3.1}$ is only partially supported.

A limitation to the experiment design was the way the conditions were presented to each participant, as they were all delivered in the same order, rather than being counterbalanced. One could argue that since each participant produces a unique physiological response to the exposure, when measured with the sensor, this would the reduce most other biases from the experiment other than fatigue. By restricting the overall exposure time to 30 minutes this would then reduce any fatigue effects.

Figure 4.18: The virtual AOP helicopter cockpit: (Back) Trainer/Assessor observing (Left) AAS Trainee and (Right) professional AOP Pilot.

4.3 Experiment 3: Decision Making under Stress

This section discusses the third experiment which focuses on integrating the psychological stress element from the pre-existing radio tasks used in the current classroom training method, with the addition of a situated simulation provided by the VRTS in a Naturalistic Decision Making (NDM) environment. We are interested in how this integrated system compares to the existing training practices currently in place for AAS and if it has an effect on physiological stress and subjective stress.

4.3.1 Hypotheses

In this experiment, we considered the following research hypotheses in terms of stress and presence:

H_1 *Using a multi-sensory VRTS (High-fidelity) results in equivalent stress levels compared to a real field-training exercise (Perfect-fidelity) as measured by the HRV physiological response.*

H_2 *Using a multi-sensory VRTS (High-fidelity) results in greater confidence compared to a radio-only exercise (Low-fidelity) as measured by the SSSQ.*

H_3 *Using a multi-sensory VRTS (High-fidelity) induces greater stress compared to a radio-only exercise (Low-fidelity) as measured by the SSSQ.*

4.3.2 Experiment Objective

The objective of this experiment, was to see if our training system, with the addition of the contemporary radio communication exercise in multi-person training scenario, was comparable to a field training exercise, as well as the radio-only exercise. In this experiment, we compared trainee AAS objective physiological data in the VRTS (Figure 4.18) and a real world field exercise training scenario using a within subject comparison. Additionally, subjective data in regards to stress using the SSSQ was captured from a similar expert end-user group, the ASS trainees who were performing the radio-only classroom exercise. Using this data, a comparison is made with using subjective questionnaire data from the AAS with the SSSQ in a between subjects comparison. By comparing these two data set types in our mixed-experiment design, we want to find out if the VRTS is more effective at creating stress than the current training conditions.

4.3.3 Experiment conditions

This experiment comprised of three separate conditions, shown in Figure 4.19 below:

(C_1) **Low-fidelity Radio Exercise**

(C_2) **High-fidelity VRTS Exercise**

(C_3) **Perfect-fidelity Field Exercise**

Figure 4.19: The training conditions compared for decision making under stress.

4.3.4 AAS VRTS Third Iteration System Diagram

The AAS VRTS system diagram for decision making is shown in Figure 4.20.

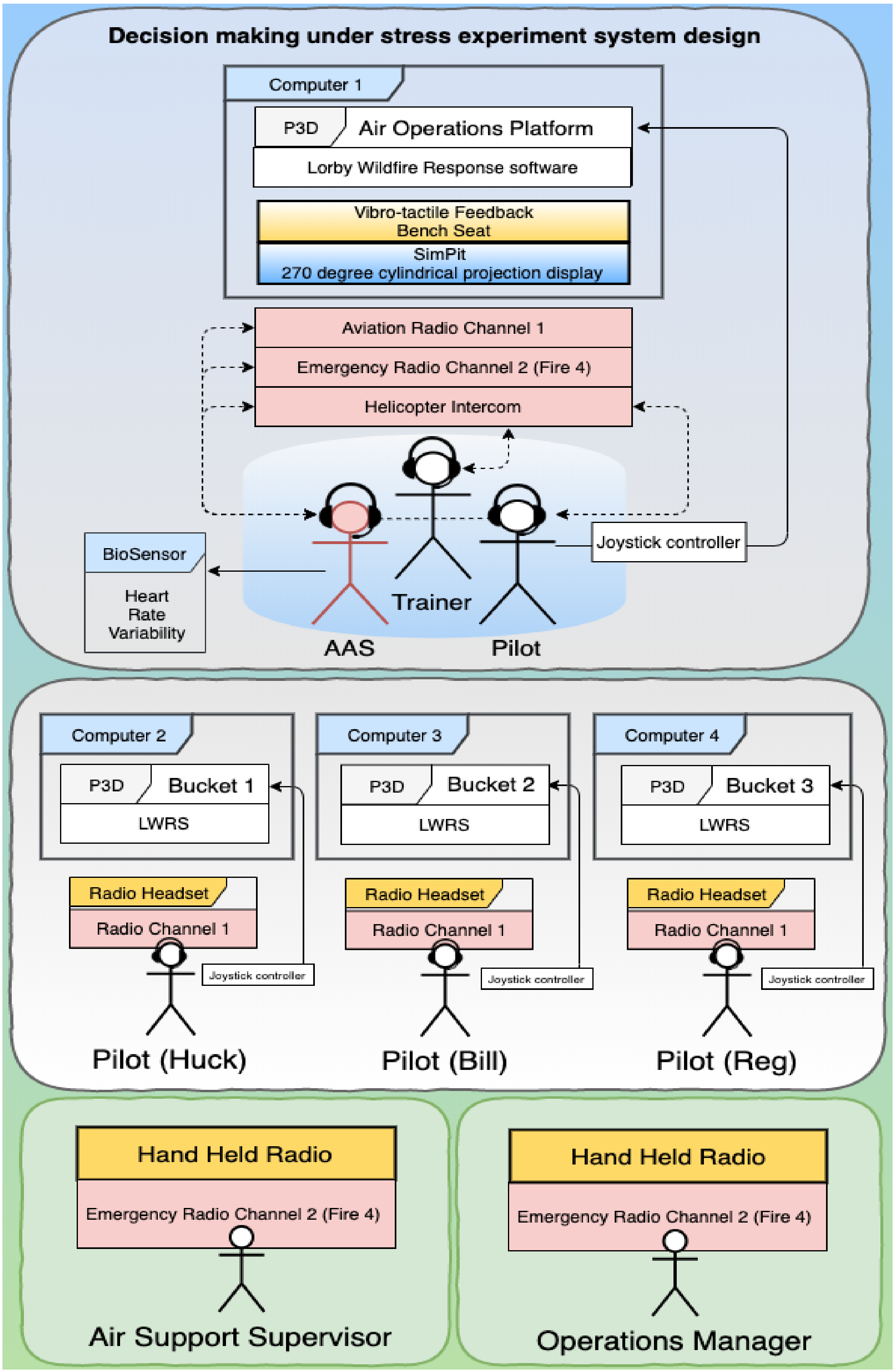

Figure 4.20: The Air Attack VRTS decision making system design.

4.3.5 Experiment Design

In order to recreate a typical fireground radio environment, four groups of three AAS trainees were created: one for AOP (including the AAS), one for ASS, one for the helicopter aircrew and one for OM.

4.3.5.1 Experiment Task

Many channels of information regarding the fireground was dynamically provided to the participant AAS who was confronted with multiple stimuli that needed a verbal response. SA was received from within the AOP, from the helicopter aircrew and from the ASS. The OM made radio requests for information called a recce or a situation report (sitrep) as well made radio injects to create stress. The aircrew (Figure 4.21) actively engaged with attacking the fire on the fireground, calling out circuits and relevant information to the incident.

Figure 4.21: The separate room for the aircrew and operations manager.

4.3.6 Procedures

In this section, the three procedures for each of the conditions are presented.

4.3.6.1 Low-Fidelity (C_1) Radio exercise procedure

The Low-fidelity condition was conducted in the same way as the procedure used for the VRTS exercise shown below (Section 4.3.6.2), except in this case, an actual fire-command unit was set up as an operations room as well, along with a separate room for the other actors (Figure 4.19 mid). The participants were rotated out of the operations room and command unit, with one acting as the AAS in the operations room. In this condition, we recorded demographics and SSSQ data.

4.3.6.2 High-Fidelity (C_2) VRTS exercise procedure

The virtual re-enactment of Gold Creek was conducted using the following experimental flow:

1. Participants randomly split into groups of three and then assigned to a role as either AAS, ASS, OM and aircrew.
2. Participant completes Pre-SSSQ questionnaire.
3. Participant fitted with physiology sensor (wait 4 min for HRV)
4. Participant performs 4 minute breathing exercise.
5. Participant enters the Air Ops Platform AOP.
6. Scenario begins, OM starts the role-play scenario (Bucketing pilots take off and get to work extinguishing fire.

7. The next AAS participant in-line completes steps 2-3 in parallel.
8. ASS, OM and aircrew pilots radio the AAS either with fireground information or radio inject and sitreps recce.
9. After 5 minutes, next participant in-line performs the 4 minute breathing exercise.
10. After 10 minutes, the participant in the VRTS swaps with next in-line.
11. Departing participant has physiology sensor removed, completes Post-SSSQ and IPQ questionnaires and open questions for qualitative feedback.
12. After three iterations, AAS groups and ASS groups swap roles, as well as OM aircrew teams swap roles.
13. After three more iterations, ASS and AAS groups swap with operations and heli-pilots, repeat process until all twelve participants receive the exposure.

4.3.6.3 Pre-Experiment Tasks

Before we conducted the experiment, we provided an informed consent form to the participants. After they agreed to the information, we randomly distributed each participant to one of four groups to play the role as AAS, ASS, OM or as Bucket Crew (BC). After collecting demographic information, the participant was asked to fill in a pre-SSSQ questionnaire that we used to form a baseline for the stress measurement. We provided a four-minute rest to get a reliable physiological signal for HRV after we attached the sensors to the participant. Before the participant entered the AOP, we gave another four-minute breathing exercise for getting a stable or resting HRV. We call this phase in the procedure the *pre-entry* step.

4.3.6.4 Mid-Experiment Tasks

After the *pre-entry* step, the participant took a seat in the AOP, and the OM began the Gold Creek scenario together with the BC and the ASS, to attempt to control or extinguish the fire. Other actors requested various information and calculations of quantities of required fuel or water, or status of pilots from the participant to generate more task-stress about fuel and other resources the AAS would need to take into consideration.

4.3.6.5 Post-Experiment Tasks

After ten minutes of exposure, the AAS trainee rotated with the next trainee. The next AAS followed the same *pre-entry* step while we removed the physiological sensors from the departed AAS. The departed participant was asked to complete post-SSSQ and IPQ questionnaires, as well as post-questions about the system including their open feedback. We iterated the whole procedure until all twelve participants had experienced the AAS role.

4.3.6.6 (C_3) Perfect-Fidelity Field training exercise procedure

The real-world field training condition was performed similarly to the same process as the VRTS condition. Participants were fitted with physiological sensors prior to entering the AOP helicopter. Three AAS participants at a time were prepped to perform the task. In this situation, the OM and AAS ground crews were fixed, due to the nature of the field training being an expensive practise.

Physiological measures of the AAS were recorded until the field task was completed. Each trainee experienced approximately ten minutes of a real AA operation using two helicopters and a fixed-wing aircraft, with ground crews, OM and AAS providing radio communications.

4.3.7 Results

This section provides the results from the stressful decision making experiment.

4.3.7.1 Participants

In this experiment, a combination of practising AAS and ASS was used with 20 years experience as a firefighter. In the AAS cohort, there was one female and eleven males, aged 47 years on average and two and a half years experience as an AAS. In the ASS cohort, there was twelve males aged 47 years on average, who had been performing the ASS role on average for seven and a half years.

4.3.8 Objective Data Results

We captured the HRV, i.e. the change in heart rate for each participant during the exposure period. A reduction in HRV shows a more rapidly beating heart, indicating a greater state of stress. This data was compared to show objective stress between the (C_2) High-fidelity and (C_3) Perfect-fidelity conditions. HRV data was collected from eleven of the twelve participants in the (C_2) VRTS condition. One participant could not get a reliable HRV reading. Seven out of the 12 participants provided reliable HRV data in (C_3).

HRV data is plotted over time (Figure 4.22, Figure 4.23), where each participant is represented by a colour and the same colour is used for both graphs. Both HRV data sets showed similar tendencies, starting with high HRV showing the rest state, slowly decreasing, then remaining steady at the low HRV level in both conditions until the data recording was completed.

To clarify the observation, we performed a 1-sample Wilcoxon test on the HRV data set at the 5% significance level, since our data did not show a normal distribution with an Anderson-Darling test. As we conjectured from the graphs, the lowest measured HRV did not find a significant difference between the multi-sensory VR condition ($Mdn = 30$) and the real-world condition (C_2) ($Mdn = 43$), $Z = -0.34$, $p = 0.735$.

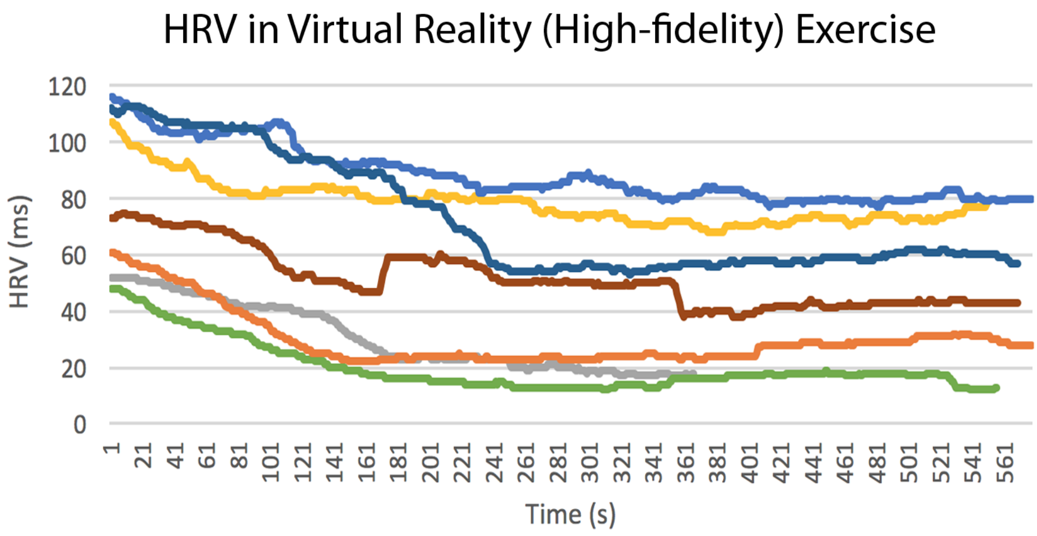

Figure 4.22: (C_2) VRTS exercise results; one colour represents one participant.

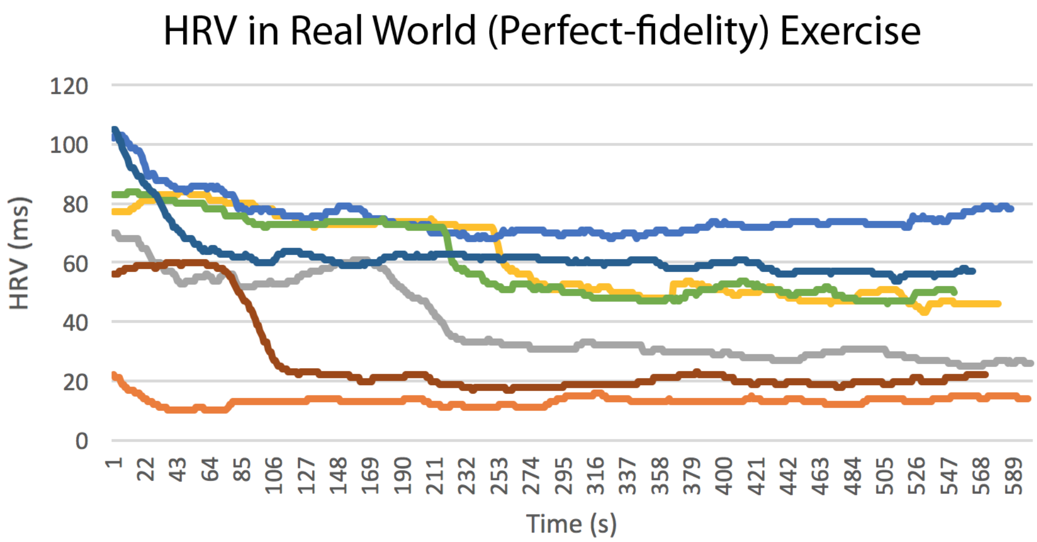

Figure 4.23: (C_3) Field exercise results. Colours are the same as Figure 4.22.

4.3.9 Subjective Data Results

This sections presents the results of AAS and ASS trainees for subjective stress using the SSSQ in the training exercise, presented graphically in Figure 4.24. Due to the low sample size, it could not be concluded that the data was normally distributed. For this reason, a non-parametric Wilcoxon Signed-Rank Test for the two constructs was used at the 5% significance level, as this test does not require normally distributed data.

(C_1) Low-fidelity Results For the low fidelity-scores we analyzed the perceived stress for each of the three categories in the original questionnaire of Engagement, Distress and Worry (Figure 4.24). For engagement, we did not find a significant difference in Pre-test for ($Mdn = 28$) and Post-test ($Mdn = 30$), $Z = -0.716$, $p = 0.474$. We also did not find a significant difference for the Distress in Pre-test ($Mdn = 9$) and Post-test ($Mdn = 14$), $Z = -1.694$, $p = 0.90$, nor for Worry between the Pre-test ($Mdn = 15$) and Post-test ($Mdn = 13$), $Z = -0.714$, $p = 0.475$.

(C_2) High-fidelity Results For the high-fidelity scores, we analyzed the perceived stress for each of the three categories in the original questionnaire of Engagement, Distress and Worry (Figure 4.24). For Engagement, we did not find a significant difference in Pre-test ($Mdn = 27$) and Post-test ($Mdn = 30$), $Z = -0.75$, $p = 0.453$. We also did not find a significant difference for the distress in Pre-test ($Mdn = 8.5$) and Post-test ($Mdn = 10$), $Z = -1.302$, $p = 0.193$. However, we found that worry significantly decreased between the Pre-test ($Mdn = 13$) and Post-test ($Mdn = 9.5$), $Z = -2.09$, $p = 0.037$ with a large effect size ($r = 0.6$).

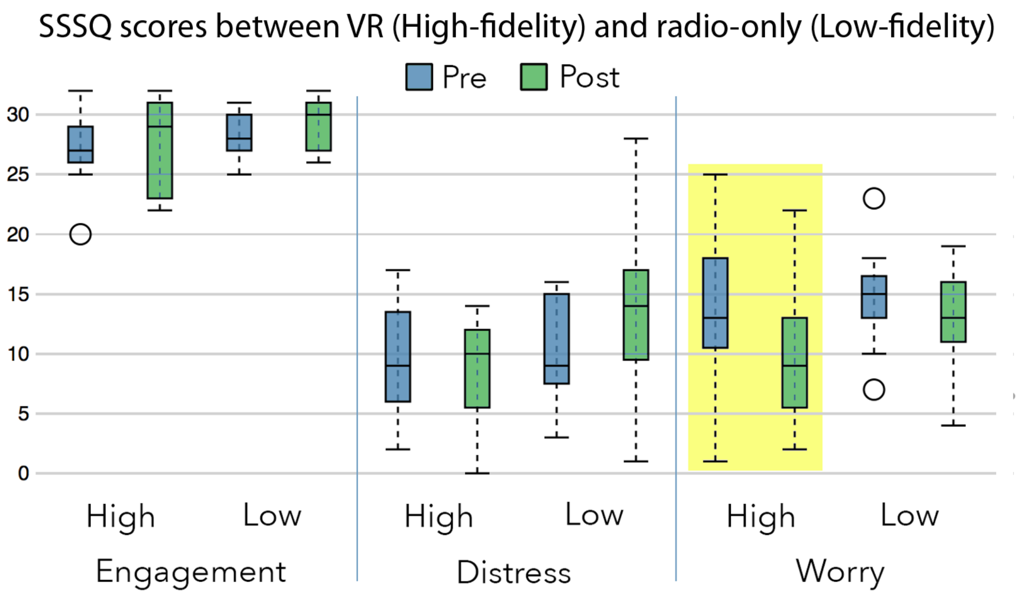

Figure 4.24: SSSQ comparison between the (High-fidelity) VRTS and (Low-fidelity) radio-only training conditions. A higher score indicate a stronger effect.

4.3.10 Discussion

This section discusses the results of the decision making experiment.

4.3.10.1 Physiological Response

Physiological data indicates that the study showed no observable differences between the VRTS training condition (C_2) and the real-world condition (C_3) in terms of HRV physiology. From the individual graphs (Figure 4.22 and Figure 4.23), we can observe that participants became stressed quicker during real-world training, which would be expected as it is a real situation and of the highest fidelity, however it could also be because of the altitude which is known to effect physiology. Also, if the participant has a fear of heights, this could also trigger a physiological response. It is assumed however that the participant would not be interested in this role if they possessed such a fear. Both training experiences had similar mean HRV scores as shown in Figure 4.22 and Figure 4.23, with a slightly later decay in HRV in the real-world condition (C_3). This could be due to the lack of danger involved in the VRTS training as well as having executed a breathing exercise prior to the exposure, resulting in a steeper reduction in HRV and a degree of calmness prior to exposure. Unfortunately, due to time constraints, it was not possible to conduct a breathing exercise in (C_3) When negating this initial time of task engagement, the HRV data showed from the two graphs (Figure 4.22, Figure 4.23), verified by the statiscal analysis showing no significant difference in the HRV in the two conditions (C_2 and C_3) that the level of physiological stress was similar to that experienced in the real-world training scenario. Interestingly, of the trainees for which HRV data was collected, two of them showed HRV results that had greater stress in the VE (green and brown). These two participants were observed to be the last two in the order to perform the VRTS exercise and had been previously participating in the radio role play, so there may have been a fatigue factor involved. One participant (Figure 4.22 brown) experienced a sudden reversal of HRV during the VRTS exercise. This could be explained by a technical hiccup being experienced with the display which needed fixing with a partial restart. It was considered to remove this participant from the data, but because of the already low participant pool and that the system could quickly be restored without having to remove the participant, the data was kept out of interest. In general, we did not observe any significantly different HRV scores, which is shown in Figure 4.22 and Figure 4.23, supporting $\mathbf{H}_1$ that VRTS training creates equivalent stress levels as measured by HRV.

4.3.10.2 Subjective Response

The SSSQ showed a significant difference for the (C_2) VRTS task which was not observed in the (C_1) task between before and after exposure in terms of Worry, but not in terms of Engagement or Distress. This suggests that while the participants did not experience anxiety with their performance, they experienced less concern or a sensation of relief post exposure. A conclusion is that the trainees felt better about themselves after being exposed to the (C_2) VRTS condition, suggesting greater confidence in their abilities. Engagement scores should reduce post exposure, however in our case they maintained engagement after the activity, suggesting eagerness to continue using the system. Distress scores show our participants did not experience a negative reaction towards using the VRTS system, perhaps with the knowledge that they were not causing any physical catastrophe by practising virtually. There was a significant decrease in the Worry category, which may be interpreted as increasing the confidence of their skills and capabilities. In this case, worry that was experienced by the trainees came from having to be evaluated to be approved for deployment during the field examination. If they did not pass the field exam, then they may not conduct the expert role. In both cases, the training took place the day before the field exercise or exam, so the existence of this performance worry was persistent between the two conditions. Since there was no significant differences in these scores for the low-fidelity radio-only condition (C_1), we can partially claim that $\mathbf{H}_2$ is supported, based on the lower post-Worry results experienced with the VRTS system. $\mathbf{H}_3$ was not supported by our results, since engagement scores were not significantly different in both high-fidelity (C_2) and low-fidelity (C_1) conditions, suggesting the radio task was just as engaging as the VRTS condition regardless of the fidelity of the system. This made sense when making observations during the study of both conditions, as participants would visibly show signs of both engagement and distress in the exercise.

4.4 Summary of Emperical Studies

The results of the three experiments are summarised in the following paragraphs followed by their limitations and how to navigate them in the future. In Experiment 1, SA was investigated in terms of visual acquisition. It was found that immersive interfaces had a significant effect on all three levels of SA as defined by Endsley [51], being the perception of elements, the comprehension of the situation and the prediction of future status. No significant difference was found between the two immersive interface types, which supported our initial hypothesis. It was noted the level of simulator sickness that was induced from the HMD was significantly higher than the HDTV and the CPD. The HDTV and the CPD were not significantly different from each other. The presence results indicated that the HMD gave the greatest presence with the VE which was closely followed by the CPD. With these results and from user feedback we deduced the best course of action to continue the VRTS design was the CPD. However, it was acknowledged that with software improvements such as 3D avatars with character rigging, further use of Artificial Intelligence (AI), voice recognition and hardware improvements such as fully integrating a VR HMD into a computerized training helmet with non-invasive physiological sensors could still make the HMD a suitable option for training in the future due to it's portability and highly immersive nature.

In Experiment 2, the communication functionality was investigated, looking at how the system can be used to induce stress-related to radio communication such as helmet-fire. It was found that as the different stressors were added, it created more complexity to the situation, having an effect on participant stress levels. The second and third phases, being added background radio chatter and disrupted communications, were significantly lower than the first phase being helicopter rotor noise, vibrotactile feedback, and standard radio communications with the aircrew. It was also found that respiratory frequency reduced with the increase in radio complexity. However, although the results showed a lower amount of radio calls as measured by the amount of PTT footswitch presses, it was not significant so this did not support the hypothesis that radio experience played a part in more effective communication. When comparing firefighters who had AAS experience versus those that did not have AAS experience, it showed that in the final phase distorted communications, that AAS were, in fact, more efficient. It was noted the effectiveness of pre-recorded radio calls which could be used as radio injects were quite useful for triggering participant response especially if the participant knows the person and rank. With a greater library of radio injects this effect could be really well utilized in personal training sessions without requiring many trainees simultaneously.

In Experiment 3, The VRTS was compared against the existing training exercises, the radio-only exercise and a real-world field training exercise. It was found that the VRTS exercise provided a significantly different result for the worry subcategory of the SSSQ, where participants felt less worried after completing the training than in the radio exercise. This indicated that the VRTS had a positive impact on their ability to recover from the training experience. The engagement and distress sub-categories showed no significant difference, so this only partially supports the hypothesis. When comparing the field training exercise versus the VRTS exercise for HRV, participants showed no significant difference between the two training types, indicating that the two types of training generated a similar level of stress, supporting our hypothesis. The trainers especially appreciated the integration of the pre-existing gold-creek radio exercise, as it enabled them to pick up the training quickly without having to re-learn the roles and the flow of the exercise. When developing further exercise experiences, it would be recommended to consult the SME again to create the content so it works for them and achieves their training objectives.

These results all show a positive outcome for the VRTS system that was developed, although the system should be further tested and increase the participant pool to draw any solid conclusions about its effectiveness.

4.4.1 Experiment limitations

By using expert-only users in Experiment 3 generally meant our participant pools were low, diminishing the statistical effect. However, focusing on the expert users in the AA domain means the experiment is of high ecological validity making the feedback from the participants very important and highly valuable. It would be highly beneficial to continue experiments with additional participants in a long term trial to improve statistical power.

A major assumption was made that stress experienced in the VRTS condition was the same as what was experienced in the real-world condition. However, there are other factors at play in the real world that affect physiology, such as altitude and physical sensations of tight, multi-axial aerial maneuvers. These factors may manipulate HRV. At the same time, the use of VR due to its novelty also has an effect on physiology, especially for first-time users. Alternative ways of recording stress would be useful such as the use of electroencephalogram (EEG) to monitor the regions of the brain responsible for communication, decision making, and other associated cognitive functions. Additionally, the use of eye-tracking for gathering information on visually acquired SA and object identification would be highly valuable for comparative purposes.

The study design was limited since we did not capture HRV data in the radio-only task, as well as not capturing stress state questionnaire data in the real training exercise. In some cases, the physiological sensor was not practical to use as it interrupted the training schedule, so often some of the measures would get dropped in favor of what was more convenient. This limitation could be easily overcome by running the exercise again with the HRV sensors in the radio task, as well as conducting the SSSQ in the real world field exercise. It was also noted the difficulty in using the chest-strap HRV sensor which failed in several cases, reducing the amount of available data for comparison. Additionally in the seated position and if the device had slipped during the real-world exercise, it was not practical to fix this during the training session, also requiring the experimenter to be in close proximity to the trainee to ensure that the data was in fact captured.

In the real training exercise, it was observed that radio chatter was not as stressful as experienced in the VRTS exercise or in the radio-only exercise, which made attempts to emulate the chaotic nature of helmet-fire at a real fire incident. This makes VRTS training more advantageous as the frustrations experienced in communication difficulties can be trained for in addition to the experience of a dynamic wildfire, albeit virtual. To perform this in the field becomes dangerous and risks fire getting out of control especially with more novice trainees.

Chapter 5

Final Discussion & Conclusion

This chapter summarises the thesis and discusses the findings and implications of the research. This thesis contributes to advancing research in the application of VRTS for high-risk emergency and disaster response, in particular to AAS. Although we focus on AAS in aerial firefighting, other complex domains or occupations operating in team-based, high-risk situations may benefit from this knowledge. The limitations of this work are discussed, with future work presented and final conclusions provided. We address the individual questions posed in Section 1.4.2 to verify if our objectives were met and how we can improve the end result in future iterations.

5.1 Discussion

In this thesis, the fundamental aspects of aviation firefighting which is known as AA was discovered. A good AAS requires a wide array of skills and abilities, such as leadership and self-awareness, are the primary skills of SA, communication and decision making under stress. This addresses the first research question $\mathbf{Q}_1$ *What* *fundamental aspects of AAS must be captured to ensure the VRTS is focused on the AAS training goals?* This is reflected in the experimentation by focusing on these three primary attributes. $\mathbf{Q}_2$ asked *What mental and physical conditions of the AAS occupation are required in the simulator to provide an immersive training experience?*. It was clear the amount of stress generated from the communications system and disrupting it had an effect on participant physiology. Recreating the stress normally experienced in *helmet-fire* was critical to create the mental stress experienced in AAS. The physical stressors were clearly evident of being motion effects, the mixed smell of burnt jet fuel and hot leather, as well as vibrations experienced from the helicopter engine and turbulence. Additional sensations of vertigo played a part but this effect is more prominent in the HMD, which was reported in user feedback. $\mathbf{Q}_3$ asked *What display technology is more appropriate for AAS VR training based off user requirements?* It was found that both HMD and CPD types have their own unique advantages, which would be useful to adopt in different training scenarios. The HMD would be optimal for users training in a home or at the station or where space is limited, as well as for practising relevant skills in personal offline training, before engaging in team exercises. By doing this would better prepare trainees for assessments which are costly to conduct, so trainee skills should be sharp by the time this happens. The CPD on the other hand makes for better assessment style usage scenarios and for expert users who need additional stimulus to be engaged. Novice trainees are more susceptible to being overwhelmed in these conditions, which was reflected in the results from Experiment 2. $\mathbf{Q}_4$ asked *What communications challenges create a stressful AA environment?* This was answered in Experiment 2 which revealed a relationship with the compounded communication stressors, background radio chatter and disrupted communications and stress, from the physiological response as well as from participant feedback. $\mathbf{Q}_5$ asked *How do expert AASs react to* *stressful conditions?* Expert users tended to manage the situation better than novices by employing CRM techniques, by trying to re-establish communications and ensure that messages were delivered to aircrew. Novice users tended to accept the situation and did not establish a new communications method to ensure their messages were delivered, resulting in less efficient communication. The last question **(Q_6)** asked *Can a VRTS create similar stress levels as a real training exercise for AAS?* This is answered in Experiment 3, by comparing subjective responses in the stress state questionnaire SSSQ for the radio-only exercise and the VRTS exercise, as well as in the HRV comparison between the field exercise and the VRTS. Both of these comparisons resulted in a positive outcome for the VRTS with the VRTS having comparable SSSQ data to the radio-only exercise but having an improved recovery for the sub-category of worry. This makes sense as the VRTS was built upon the radio-only exercise and integrated it effectively in the exercise. The greater presence that participants experienced could have led to a better learning outcome, reducing the level of worry post exercise. The real-world field exercise and the VRTS training resulted in similar physiological responses, however it was difficult to tell if the types of stress being experienced were the same in nature. Further experimentation is desirable with other measurements of recording to include the SSSQ in the field training exercise as well as more accurate Electroencephalogram (EEG) physiological measurement to identify the regions of the brain being stimulated in training.

The contributions of this thesis enhance current knowledge of how VRTSs influence occupational stress, task performance and higher cognitive skills like SA or decision making, and how this technology can be used to train AA firefighters in Aotearoa, New Zealand. A VRTS could also be applied to train for AA globally with minor modifications, as well as a variety of training in emergency and disaster response and high-risk occupations involving complex NDM. The importance of this research was introduced in Chapter 1 and how this research is performed following UCD strategies. Chapter 2 provided background knowledge of the problem domain and related work that influenced the research. Chapter 3 presented our independent user research, design methodology and design iterations followed from user feedback and experimentation. Chapter 4 presented the results of the empirical studies performed based on the user research.

Literature for the use of VRTS in complex environments was presented in Chapter 2, where aspects of decision making in naturalistic environments was investigated. This highlighted the necessity to consider the psychological state of trainees and how stress has an effect on the mental and cognitive ability of decision makers in complex environments. It was discussed what effect that stress has on decision making, communication and memory and how the brain responds to stress and other negative operator states. It was shown how this also takes an effect on the physiological state, which can be measured by electrical signals.

Following this, there was a discussion about the value of SA to team-based organisations, particularly to aviation-based occupations, including AAS. It was shown to have a complete SA, three levels of SA must be achieved. Firstly, perceiving the elements of a complex situation is necessary to build a baseline understanding of a given operation. Secondly, comprehending what the elements are and how they influence the situation needs to be established. Finally, people need to have the ability to predict the outcome of the situation based on the perception and comprehension of the elements involved, in order to obtain a more complete picture of SA. This higher level cognitive function requires a positive operator state, unabated by stress or anxiety. High quality SA is necessary for ensuring safety and effectiveness in real NDM environments.

Aspects of CRM were presented, where it was highlighted how effective teams utilize high quality communication and teamwork as the keys for effectiveness.

This showed how interpersonal skills and interoperability between teams and organisations that require multiple crews in different roles make for more effective outcomes in real-world situations in emergency or disaster response. Leadership is important to ensure these factors are maintained by all team members and to allow colleagues to speak up if they are uncertain or see something that does not seem right. Communication is fundamental for effective teamwork, where many issues in complex situations can be remedied by improving communications. To improve real-world handling of situations, communication protocols should be frequently maintained and integrated into training to be able to handle communication errors from either mechanical or human origin.

Many different high-risk, high-stress occupations may benefit from SBT, to practice for particular events that are complex in nature. AA in this particular case requires a suite of advanced cognitive, team-based training tools to be implemented to create task relevant stressors that are related to SA, communications and decision making in a naturalistic environment. This allows regular opportunities for expert operators needing to maintain essential psychological and cognitive skills to conduct aerial operations in wildfire fighting in rural environments. As cities and towns become more densely populated, the human population spreads further into rural land, building housing closer to areas at-risk of wildfires in a region known as the RUI. This puts their lives at risk of wildfire as they are likely to lose property, livestock, possessions or be susceptible to injury or even fatality. Under these conditions the AA operation is to reinforce the ground crews to combat the fire as a multi-lateral HRO. Ultimately, it's the boots on the ground that put the fire out, but together with the aerial assets to prevent severe ecological damage occurring. This is done by beating the fire fast, safely and efficiently, before it becomes out of control an un-manageable.

Other critical and complex occupations in the emergency domain can include other natural disaster response for occurrences such as volcanic eruptions, floods, hurricanes and other severe weather situations. Man-made disasters can also be practiced for, such as nuclear power plant failures, toxic and hazardous material spills, off-shore disasters like deep sea oil rigs and sinking ships. They can happen in either urban, rural or at sea, but in most cases have a human element which requires difficult decisions to be made on the spot involving people's lives. In some cases, endangered species and purebred livestock may need to be abandoned, as well as people themselves may need to be left behind due to lack of space in extraction vehicles, reducing their likelihood of survival. Having to make these kinds of decisions is difficult to say the least, having both short term and long term psychological effects on the decision maker. This may cause the fight-or-flight response to be over-stimulated with acute stress, Critical Incident Stress (CIS) and decidophobia creating a delay in the decision making response time.

The user research conducted supports this, along with our findings in relation to the fundamental aspects of aerial firefighting. These aspects are focused on in the design of the VRTS for AAS, specifically SA, communication and decision making in a complex team-based environment. This user research instigated the initial experimental design and development of the prototype VRTS.

Data from three empirical studies was collected and analysed with statistical hypothesis testing. The evidence of the iterative development shows that the inclusion of the end-user greatly aided the final result and enabled their existing training practices to be acceptably augmented with the technology.

SA and Presence in a VE was higher with more immersive interface devices as discovered in Section 4.1 across all three levels of SA, suggesting immersive displays should be preferred for creating greater task presence by increasing potential stressors and occupationally-relevant stimuli. SA was significantly greater in the immersive displays over the more commonplace HDTV display type. However, no significant difference in terms of SA was found between the two immersive display types. It was shown that the HMD created a greater sense of Presence as well as simulator sickness than the projection display, suggesting this was a more immersive display type, but was not any better at providing SA compared to the surround projection display. It was clear that the level of simulator sickness using the HMD was significantly greater than both the HDTV and the surround projection display, making this method of content delivery less appealing for long periods of exposure or requiring more frequent exposure for acclimation. The projection display also afforded a better co-pilot experience, by having greater (physical) connection to the aircraft pilot.

With this knowledge, it was decided to utilize the CPD as the display type for future iterations, as the AAS is generally required to be in operation for long periods of time and needs to have direct interaction with the pilot, giving a greater sense of Presence. This was explored in Section 4.2, where the prototype was further developed to include greater sensory feedback by including occupationally relevant audio and haptic stimuli. Haptic stimulus in the form of a vibrotactile bench seat was added to enhance the presence and realism of the helicopter cockpit environment. A typical radio environment was implemented and shown to provide occupationally relevant stressors when training in the VRTS, revealing a change in physiology when compounded. This was measured objectively with HRV using a wireless physiology sensor and subjectively with questionnaires that were completed by participants at a variety of skill levels.

More experienced personnel were able to utilize the VRTS more effectively when the additional stressors were present, suggesting this system would be suitable for re-creating a high stress NDM environment, typical for the more experienced AAS firefighter. We explored this in Experiment 3 in Section 4.3, which compared the augmented radio training with the existing training practice methods, being the radio role-play exercise and in the field exercise, to create a high degree of psychological stress in a team-based environment. Based on the user feedback, the vibrotactile bench seat was redesigned to include foot rests that were connected to the base of the bench seat. This made the seat more immersive as vibrations were felt through the whole body, better emulating the vibrations experienced in a normal helicopter. In the previous experiment, participant legs were on solid ground, reducing the presence with the simulator.

It was discovered in the final study that the subjective stress state sub-category of *Worry* of the Dundee SSSQ was significantly higher in the high-fidelity virtual training over the low-fidelity radio exercise. This suggests that the VRTS created a greater degree of cognitive risk analysis. This factor is essential for avoiding potential threats or for problem solving, both of which are critical to the AA domain to ensure team safety and effective operations. Additionally, a comparison of HRV was made with field training exercises and found to create a similar degree of stress when performing AAS. Stressors were much more easily manipulated in the laboratory environment, while doing so in the field would lead to increased physical risk. This final study opened insight into future work explored in Section 5.4.

5.2 Contributions

The main contribution of this thesis is the creation of a design of a VRTS, specifically for augmenting existing training in aerial firefighting. This provides evidence to support higher cognitive function in a safe NDM environment for experts as well as for novice users. The implications of this may benefit other domains as previously specified. The UCD approach used and BRM may also be applied to other similar areas of expertise requiring training and integration of complex, multi-skilled, cognitively and physically demanding environments.

This work shows how to integrate VR technology into training in aviation firefighting for SBT. This is a highly understudied research domain, which makes this research a valuable contribution to this space. It was shown that the usability of a VRTS can be significantly improved by following the UCD strategy, by incorporating user feedback into the design iterations and focusing on the goals of the end-users. It was shown that it is not necessary to implement excessive amounts of physically immersive elements, but to focus more on the psychological immersion, in order to create enough task-based stress. Facilitating psychological stressors and increasing bandwidth of relevant task-based information through visual, auditory and vibrotactile sensory channels enabled a NDM environment for practising aerial firefighting scenarios. This was demonstrated in Section 4.3, where the same radio exercise normally undertaken without any computer-based technology, was achieved also with the VRTS, providing a situated training environment. This is especially good for trainers as they can easily practice the same radio exercise as normal and focus on providing psychological stimulus. This is beneficial for trainers as it means that they do not need to retrain themselves to work with the technology, making it more seamless in its design.

5.3 Limitations

The participant pool was made up of mostly male participants, who, according to Bos et al. [22], become slower in decision making when under stress, becoming more risk averse and are at greater risk of chronic stress. Females on the other hand are inclined to make faster decisions when under stress, but may be more effected by social rejection when making decisions than males. Further investigation into the differences of males and females would be beneficial to verify this in AAS. Wemm et al. suggest that males take greater risk when under stressful conditions [145]. Generally having a limited participant pool was a disadvantage to the statistical analysis. This could be overcome by conducting further studies following the same design to enhance the statistical evidence and create a long-term study. It would also be valuable to identify other performance metrics and study these over time, to find out specifically if the VRTS is in fact achieving greater training outcomes.

Since VR is novel in nature, this may inadvertently effect the subjective response of the trainees, creating bias in questionnaires. In some situations, if the fire got out of hand in the VE, it would cause frame-rate issues, providing a lower quality training experience as well as simulator sickness. More refinement to the hardware and software to create a more stable system would be needed to reduce these limitations.

In Experiment 2, the experiment assistant, who was controlling a helicopter, had a thick french accent, which could have effected some participants ability, creating an additional stressor. Both the experimenter and assistants were not fully trained pilots and made a best effort attempt to follow aircraft radio protocol. Having real pilots or receiving adequate training in aviation would provide a more realistic training environment. This would greatly benefit the AAS VRTS to improve the presence.

Further measurements could have been integrated, such as eye tracking, speech pattern recognition or recording video of user responses, as a way to measure performance and user behaviour. For these studies, self-reported questionnaire results and physiological sensors measuring HRV were relied upon to measure stress. While HRV can be used to show stress, it is difficult to tell if this is perhaps measuring presence and can be effected by other aspects like physical motion, or even a change in altitude. Measuring cortisol would have also been beneficial to verify the stress response, however this method is slightly invasive. Further research using EEG would be valuable to understand if the training system is having a cognitive effect by providing the right training stimulus and enough stress for inoculation training. It would be interesting to utilize EEG technology to measure physiological response as well as cognitive workload, by analysing the activity from the respective regions of the brain in either a training application or a real world situation.

5.4 Future Work

This thesis provides the groundwork for utilizing immersive VR technology as a training system to augment and support AAS training. This has opened up more research opportunities that can be conducted using this system, as well as future design iterations supporting technological growth, following the design methodology. The identified areas of future work include refining technological hardware and software development, elements of physical immersion and multi-sensory experiences, physiological and psychological immersion and the application of VRTS to alternative expert domains of high-risk. These are discussed below.

Further investigation into HMD-based VR is in demand from end-users due to its portability, reduction in costs and improvement in the quality of head tracking, screen resolution and level of detail. Its portability gives it an advantage which enables it to be deployed in remote locations, quickly set up in ad hoc training facilities or potentially for at-home use or where space is limited. Comparatively for projection based VR, it is still constrained by space, requiring a dedicated facility. Although it may be installed onto a mobile vehicle, this will drive up costs for the end-user, making it less feasible. From our observations and existing research, HMD-based VR can have a profound effect on both presence and stress.

This makes it a viable avenue for further development and research investigation to see how effective the training would be in the HMD, however both software and hardware technology needs to be improved to become more stable and to optimize the user experience. In saying this, both HMD and CPD immersive display styles have their benefits, where the HMD is better for personal use to gain familiarity in one's own time, while the CPD can be better used for assessment purposes and team training. It would be a good idea to further develop both display systems for greater training and assessment opportunities. Additionally certain people are more prone to simulator sickness than others, especially those who have not as much experience with computer games and VEs. The CPD was more forgiving in this regard. People who have not had much experience with VR might not be willing to use such an HMD which would result in the loss of a potentially good candidate. HMDs have a greater ability to support widescale deployment and could enable training at a greater scale. However certain improvements need to be made to improve the usability and to reduce simulator sickness. Software designers for flight simulators need to acknowledge the desire for HMD usage and design their systems appropriately, integrating player and character models inside the cockpit that provide co-pilot/pilot experience rigged with hand tracking and facial expressions to improve system presence.

Another hardware-based future design iteration is the integration of the flight helmet, with either the VR HMD or surround CPD. This would help further improve the simulation presence as communication audio would come directly through the helmet communication system, giving a much more realistic sensation of the AA experience. In the case of the HMD, it could be attached to the helmet in such a way that it could be easily flipped up or down, so that the user can quickly jump in and out of the simulation. The current method of wearing a HMD is difficult due to the head-straps needing to be adjusted for each user and also creates a weight distribution problem, whereas the helmet would fix many of these issues and would create more seamless integration of the technology. The user would have fewer issues with fumbling around with the device and could quickly gain presence with the system, instead of the technology inhibiting the process of gaining presence.

Greater haptic and vibrotactile feedback stimuli can go beyond simple engine vibrations and into tight maneuvers and the abrupt motions experienced in aircraft by turbulence or updrafts experienced from hot air rising from the fire. Although full motion simulators with six-axis tilt and rotation exist, this sort of technology could be determined as unnecessary for AA training, requiring semi-permanent infrastructure and may be more overwhelming physically, diminishing the psychological engagement and reducing the learning experience for more novice trainees [133]. Although not to be dismissed, simple motion platforms may afford a near enough experience that would be satisfactory for training, more portable and require less space than a full flight simulator. If the effect of multi-sensory elements can be dynamically scaled, this would prevent the system overwhelming novice trainees and alternatively afford experienced trainees a better sensory experience, catering for all types of trainees.

The interface for the radio system could be more natural or closer to a real-world equivalent, as this is a User Interface (UI) that is often interacted with, along with the gauges associated with airspeed, fuel, engine speed, directional gyro/compass or GPS maps amongst many sources of information that is present in the instrument panel in the cockpit. The multi-channel radio system is a complex interface that can handle multiple emergency firefighting radio channels and aviation channels simultaneously. The radio console UI can be either digital or analogue, using switches and buttons to interact with to adjust volume or change frequency, mute etc. If these elements were included in a part of the system, then it would be a more natural cockpit experience, providing greater immersion with the VRTS and creating a higher information bandwidth with the VRTS.

Radio communication disruption could be handled differently to create a more natural radio experience. Radio quality could have a diminishing effect when at certain distances away from other radio users or if obstructed by solid structures. If the distance was calculated between the radio users in the VE, radio effects such as static noise and broken transmissions could be determined by this, as well as the topology in the VE to give more realistic radio conditions. It would also be interesting to build into training a way to determine or rank the SA gathering techniques as well as radio communication between participants in such a way that it can be evaluated and produces a score or measurement of ability in order to track performance. This would help trainees practice high quality radio protocols and leadership responsibilities which are necessary in a real high-risk situation. To further this, it would be interesting to develop a handheld equivalent that could connect to the computer generated radio channel. It was noted that with the computer generated radio environment it was difficult to replicate an actual radio with all of its quirks. For this reason it would be equally as interesting to continue using real radio systems but lower the power of the radios or use thicker or more dense walls that inhibit radio transmission, so a similar effect is experienced to that of long-range radio transmission.

An important aspect of team training is listening to and participating in briefings to establish CRM. These could easily be both provided in virtual briefings, where 360° video could be captured on how to behave around helicopters and how an aerial operation is to be conducted, the airspace where both fixed-wing aircraft and helicopters operate and their respective circuit or flight paths. By understanding and practising these principles, it would help reduce stress in real world situations and is important to ingrain into trainees to avoid confusion in the airspace and a potential safety hazard. Virtual briefings can both be used to deliver content to trainees as well as give them an opportunity to practice giving briefings, which they would be expected to do when acting in a leadership role such as the AAS, ASS or OM. Gamification techniques could be applied with different levels of mastery, from rookie level to intermediate and high level mastery as a part of the training to establish healthy habit formulation, good communication, stress management and proficiency with the tasks.

Greater presence could be achieved with further natural interactions with the VRTS. Hand tracking for example can afford a more natural way of expressing directions to the AOP pilot by using hand signals or gestures captured as data, which is a standard way of communicating inside the AOP cockpit. This data could be sent over a network as data to a remote pilot, so that they may see the indicated gesture, rather than solely relying on spoken words. It could also be used to issue instructions to an AI pilot inside and outside of the AOP, such as what direction to fly in, or what landmark to circle around or what location to attack. Speech or voice recognition software could also be utilized and computed in real time in such a way to give instructions to AI pilots. This capability would greatly enhance single person training, as it would not rely upon other humans to participate in the training if unavailable. Having a combination of eye tracking, hand gesture tracking and speech recognition will greatly enhance presence with the simulator and would require less manual interaction from the experimenter/instructor to co-ordinate an air operation.

Lastly, in regards to multi-sensory immersive experiences, it would be interesting to investigate the effect that olfactory stimulus has on memory recollection and whether using smell emitters to replicate scents found in operational environment in the training environment have an effect on memory and training skill transfer. That is, if the smells that are normally encountered in a real situation are used in a VE, does this give better active recall of the protocols that should be utilized by experts? Theoretically, if this was the case, then the training would be more effective, leading to shorter response times, especially for situations or occupations that try to operate within the golden hour of response, that is the period of time to effectively contain a fire early on before it becomes widespread and un-manageable. Having a pre-exposure to certain smells may prepare trainees for situations and allow them to make faster decisions.

It would be highly beneficial to improve on the statistical significance and quality of the results by having a greater pool of participants by performing further experimentation and longitudinal evaluation. This process may also capture more firefighters interested in aviation firefighting, as the system allows for better pre-training experience without intense exposure and without the potentially off-putting CIS or the sink or swim experience. This also affords visibility within the general public, useful as an on-boarding or recruitment process, engaging with potential firefighter candidates early in their career development, tracking their progress and providing quality feedback.

Ideally, trainees could practice independently with AI prior to team training events in a personal way, so that they may practice communication skills without the stress or logistical challenge of meeting up with peers. It would be beneficial to explore single person training with intelligent feedback and re-creating the team-based training experience in VR with AI counterparts for briefings and operations etc. using real-world wild-fire AA radio chatter intelligently combined with the VRTS. Using speech and voice recognition software could be used to categorize certain phrases to provide correct radio response from AI and can help analyse the patterns of communication behaviour to find areas of improvement like confidence to be more efficient with communication.

Eye tracking data could be used for monitoring a variety of physiological and stress sate functions, as well as to provide further information about where participants are focusing, if they are scanning enough of the environment with their eyes or just looking at certain spots. The motion data captured from eye tracking and error rate can be used to analyse effectiveness. It would also be interesting to compare real fire event HRV to what is being experienced in the laboratory. It would be interesting to look more in detail of waveforms produced during episodes of heart rate arrhythmia, especially when the system is more developed to include more immersive features that create stress in the cockpit.

Applied training and commercialisation In order to fully deploy this system in such a way that it is used more frequently, the system must now shift from the prototypical *"Minimal Viable Product"* stage and into a business development model or commercialisation phase. This must be done in order to make the training sustainable. Steps that would need to be taken to make this happen should include government buy-ins and to make the system more visible to the public, so they are aware that this advanced type of training is being utilized. Additionally, the system must undergo a process of widespread industry deployment, taking it out of the laboratory environment and putting the technology in dedicated key locations to reduce logistical challenges for trainees. This would best be done by commercializing and licensing the relevant software. In this regard, a company should be established to manage the maintenance and complexities of the system (hardware and software) while working with SMEs to create targeted content. Further rigorous development of scenarios that target the identified skill gaps with trainees is also required to reach a level of functionality to supplement the standard training and assessment processes already in place by FENZ. Much like VRTS is already embedded in aviation training, where simulator flight hours are logged against pilots prior to operating large passenger jet aircraft, the system for AA training must also reach a level of functionality that can support this for accreditation purposes. This would involve obtaining current SME knowledge to shape the accreditation goals, which would also help the trainers tailor better and targeted training for each trainee. Further collaboration with other jurisdictions and countries to establish a global competency would be very beneficial especially considering the overlap in fire seasons, where experts operators from other countries can be recruited to fight wildfires outside of their normal jurisdiction. This would also help with maintaining competency between aviation firefighting around the globe. It would be beneficial for personal development and for research purposes to establishing an online currency maintenance system for trainees to track progress and to show they have reached a standard of simulator training, before they can engage in real-world field training exercises. Ideally, creating a standard for training that can be used to gain flight hours similarly to pilots. This would help experts to maintain a certain level of currency to enable offline and remote training, overcoming logistical issues, and providing a mechanism to recruit competent aviation firefighters around the world as needed. Governments and respective emergency response agencies need to acknowledge the benefit of SBT, by putting more funding towards this type of training. The outputs of this PhD research could help to drive this. Other natural disasters that can be adopted into SBT would prove beneficial to the longevity of such training system and help to make the funding go further, but must maintain the user centered approach.

5.5 Conclusion

Simulation technology is maturing at a rapid rate and becoming more applicable to numerous high-risk domains, but the focus must be made towards the psychological objectives and learning outcomes in order for them to be effective. Technology can be applied more effectively when following UCD processes and the Braided River Model (BRM) to combine multi-disciplinary domains.

The crucial components of AA were identified following a UCD development methodology. The BRM provided an overarching research strategy that ensured the crucial components were integrated into the VRTS, working in synergy and constraining the design to the identified key domains.

This thesis has presented an approach to simulator design for the complex domain of AA aerial firefighting. It was shown in the case of aerial firefighting, how the identified major tasks of SA, communications and decision making can be integrated into the system design. In the three experimental studies of iterative design, it was shown that the major tasks can be trained for more effectively when using multi-sensory technology, designed around the user. SA was better afforded when using an immersive display, which also improved presence and attributes to feelings of stress. Communication challenges can be easily reproduced, providing greater stress in training, that can be scaled as necessary. NDM situations can be easily reproduced in the VRTS, creating a level of stress similar to that experienced in field exercises, without the issues of logistics, costs and safety.

In conclusion, this research shows that VRTS can be an effective tool to augment existing training in expert NDM domains, however there still leaves a lot of room for improvement and further evaluation. Further longitudinal research would be beneficial to see if any transfer effect has taken place. It would also be interesting to allow novices access to see if these types of high-risk occupations are right for them. This system could be used for on-boarding recruits, skill maintenance or currency. This technology also has the potential to increase training opportunities, used prior to field training exercises, team building exercises, waiting on standby and as a general maintenance tool for practising high level cognitive team based tasks. This thesis has shown how a VRTS can be integrated into a complex high-risk emergency domain by utilizing UCD to focus on end-user training objectives.

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Appendix A

Experiment Content

A.1 SME Semi-structured Interview Questions

The following document is a set of questions intended to be used to guide a semi-structured interview. The questions are designed to create a flow of conversation with the interviewees, being subject matter experts. An audio recorder will be present to record the interview. They are invited to provide as much information as they can and are free to expand upon topics during the conversation. The interview will take no longer than 1 hour per person.

Air Attack Supervisor

Subject Matter Expert

Semi-structured Interview Questions

1. What are the goals of Air Attack fire suppression?

2. What are the most demanding aspects of this role?

3. How many years of firefighting experience do you have?

4. a) How many years of experience in Air Attack?

   b) How many fires have you fought in Air Attack?

5. How many people have you trained in Air Attack?

6. a) How confident do you think you would feel in the Air Attack role yourself?

Not Very Confident			Neutral			Very Confident
1	2	3	4	5	6	7

   b. What makes you feel this way?

7. What do you think are the major challenges for Air Attack Supervisors?

8. a. Does stress have an effect in Air Attack?

b. What about other Mental Factors?

9. a. Can you name some things that can go wrong in Air Attack scenarios?

b. What are the main causes of this?

c. What are you doing to prevent things from going wrong?

10. On a scale of 1 - 7, how much do you feel your effectiveness suffers from lack of practice or time on the task?

Not a lot			A little			A Lot
1	2	3	4	5	6	7

11. a. Do you have any fears when performing this duty?

12. a. On a scale of 1 - 7, how mentally prepared are you when you go into a fire as an Air Attack Supervisor?

Very unprepared			Neutral			Very prepared
1	2	3	4	5	6	7

b. Why do you feel this way?

The Following Questions are in Regards to training others for the role of Air Attack Supervisor.

13. On a scale of 1 - 7, how well do the current training methods work?

Not Very Well			Neutral			Very well
1	2	3	4	5	6	7

14. What percent of trainees pass Air Attack?

15. What do you think affects pass rates?

16. What are some of the good aspects of current training methods that you would like to maintain?

17. a. Are there any bad aspects of current training methods you would like to see improved?

b. Are there any aspects of current training missing?

18. What are the major challenges in training firefighters for the Air Attack?

19. a. Do you currently train for stress management?

b. Do you practice any mindfulness or emotional intelligence strategies?

20. What are your main objectives when training firefighters in Air Attack Supervision?

21. What are the crucial elements to understand when performing this role?

22. What methods do you use to improve situational awareness?

23. What strategies do you employ to be more effective in this position?

With these thoughts in mind, imagine you have access to a Virtual Reality Training System. This system allows you to train endlessly for any situation or scenario you can think of.

24. What scenarios or situations would you like to prepare trainees for?

25. How would you utilize this system?

This next document is a short questionnaire to get to know more about the Air Attack Trainee's, who are typically rural firefighters from various New Zealand Rural Fire Authorities. The system is ultimately designed around their specific needs and requirements to pass the course. This trainee questionnaire should take no longer than 10 minutes.

Air Attack Aerial Fire Suppression Supervisor

Trainee Questionnaire

1. Gender? M / F

2. What age range are you within?

   20-25 26-30 31-35 36-40 41-45 46-50 50-55

3. How many years have you been in the Fire Service?

4. Have you done Air Attack before, if yes how many years?

5. How confident do you feel performing this role?

Not Very			Neutral			Very
1	2	3	4	5	6	7

6. Why do you want to be an Air Attack Supervisor?

7. What do you think is the hardest part about this job?

8. Have you had any other specialized roles before and if so, can you list them?

9. Have you used Virtual Reality before? Yes / No

10. Would you consider a Virtual Reality training system as a supplement your training? Yes / No

A.2 Experiment One Supporting Material

A.2.1 Latin Square Order Display vs. VE

Participant	Condition 1	Condition 2	Condition 3
1	SimPit_PH	HMD_HA	Screen_ON
2	SimPit_A	HMD_ON	Screen_PH
3	HMD_PH	Screen_A	SimPit_ON
4	HMD_ON	Screen_PH	SimPit_A
5	Screen_PH	SimPit_A	HMD_ON
6	SimPit_ON	HMD_PH	Screen_A
7	HMD_A	Screen_ON	SimPit_PH
8	SimPit_A	HMD_PH	Screen_ON
9	Screen_A	SimPit_ON	HMD_PH
10	Screen_ON	SimPit_A	HMD_PH
11	Screen_A	SimPit_PH	HMD_ON
12	HMD_PH	Screen_ON	SimPit_A
13	HMD_A	Screen_ON	SimPit_PH
14	Screen_ON	SimPit_A	HMD_PH
15	Screen_PH	SimPit_A	HMD_ON
16	HMD_ON	Screen_PH	SimPit_A
17	Screen_A	SimPit_ON	HMD_PH
18	HMD_PH	Screen_ON	SimPit_A
19	Screen_ON	SimPit_PH	HMD_A
20	SimPit_PH	HMD_ON	Screen_A
21	HMD_ON	Screen_A	SimPit_PH
22	SimPit_PH	HMD_A	Screen_ON
23	SimPit_ON	HMD_PH	Screen_A
24	SimPit_A	HMD_PH	Screen_ON
25	Screen_A	SimPit_ON	HMD_PH
26	HMD_A	Screen_ON	SimPit_PH
27	HMD_PH	Screen_ON	SimPit_A
28	SimPit_ON	HMD_PH	Screen_A
29	HMD_A	Screen_PH	SimPit_ON
30	SimPit_ON	HMD_A	Screen_PH
31	HMD_ON	Screen_PH	SimPit_A
32	SimPit_PH	HMD_A	Screen_ON
33	SimPit_A	HMD_PH	Screen_ON
34	Screen_PH	SimPit_A	HMD_ON
35	Screen_PH	SimPit_ON	HMD_A
36	Screen_ON	SimPit_A	HMD_PH

A.2.2 Questionnaires

Survey Questions for Situational Awareness Task

The following questions will be created on the UC qualtrics website to evaluate the user experience for the experiment.

1. System Usability Questionnaire

This survey is widely used in Research Science Community. Its goal is to measure usability of a system[1]. For each of the three conditions in this experiment, we use the following ten questions that are rated using a Likert scale from 1- 5 with the responses "Strongly Disagree"(1), "Disagree" (2), "Neutral" (3) , "Agree"(4) and "Strongly Agree" (5).

1. I think that I would like to use this system frequently.
2. I found the system unnecessarily complex.
3. I thought the system was easy to use.
4. I think that I would need the support of a technical person to be able to use this system.
5. I found the various functions in this system were well integrated.
6. I thought there was too much inconsistency in this system.
7. I would imagine that most people would learn to use this system very quickly.
8. I found the system very cumbersome to use.
9. I felt very confident using the system.
10. I needed to learn a lot of things before I could get going with this system.

2. NASA Task Load Index (NASA TLX)

This survey is widely used in Research Science Community. Its goal is to measure the workload of tasks[2].

For each condition in this experiment, we use the following six questions that are answered using a likert scale from Very Low (1) – Very High (5) unless otherwise stated.

1. Mental Demand: How mentally demanding was the task?
2. Physical Demand: How physically demanding was the task?
3. Temporal Demand: How hurried or rushed was the pace of the task?
4. Overall Performance: How successful were you in accomplishing what you were asked to do? Perfect (1) – Complete Failure (5)
5. Effort: How hard did you have to work (mentally and physically) to accomplish your level of performance?
6. Frustration: How irritated, stressed, and annoyed did you feel during the task?
7. Content: How content, relaxed, and complacent did you feel during the task?

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[1] Brooke, J. (1996). SUS-A quick and dirty usability scale. *Usability evaluation in industry*, *189*(194), 4-7

[2] Hart, S. G., & Staveland, L. E. (1988). Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research. *Advances in psychology*, *52*, 139-183.

3. IGroup Presence Questionnaire (IPQ)

IPQ was developed and tested in several papers[3]. Its goal is to measure the sense of presence experienced in a virtual environment. This evaluation will use the questions that are focused on Realism Subscale. For each of the three conditions, the following questions are to be answered in a likert scale from 1 - 5:

1. How real did the virtual world seem to you? Not very (1) – Neutral (3) - Very (5)
2. In the computer generated world I had a sense of "being there" Fully disagree (1) - Neutral (3) - Fully Agree (5)
3. Somehow I felt that the virtual world surrounded me. Fully disagree (1) - Neutral (3) - Fully Agree (5)
4. I did not feel present in the virtual space. Fully disagree (1) - Neutral (3) - Fully Agree (5)
5. I was completely captivated by the virtual world. Fully disagree (1) - Neutral (3) - Fully Agree (5)
6. I had a sense of acting in the virtual space, rather than operating from outside. Fully disagree (1) - Neutral (3) - Fully Agree (5)
7. How much did your experience in the virtual environment seem consistent with your real world experience? Not at all (1) – neutral (3) – A lot (5)
8. How Real did the virtual world seem to you? Not at all (1) – neutral (3) – A lot (5)

4. Adapted IBM satisfaction Questionnaire

IBM Company showed and published this questionnaire in the International Journal of Human-Computer Interaction[4]. This evaluation will use a selection of questions from this questionnaire that are covered in other surveys. They will be rated using Likert scales from; fully agree (1) – neutral (3) - fully disagree (5).

1. Overall, I am satisfied with the ease of completing this task.
2. Overall, I am satisfied with how easy it is to use this system
3. It was simple to use this system.
4. I can effectively complete the tasks using this system.
5. I was able to efficiently complete the tasks using this system.
6. I felt comfortable using this system
7. The interface of this system is pleasant.
8. Overall, I am satisfied with this system.

[3] http://www.igroup.org/pq/ipq/index.php

[4] Lewis, J. R. (1995). IBM computer usability satisfaction questionnaires: psychometric evaluation and instructions for use. *International Journal of Human-Computer Interaction*, *7*(1), 57-78.

5. Adapted Positive and Negative Schedule5

Developed in 1988 for clinical and non-clinical trials especially to those regarding stress and emotions. These words describe a persons feelings or emotions in regards to the system The scale is a 7 point scale from 1 – 7 from not at all (1) to extremely (7). Indicate the way you feel right now in regards to the following list of words.

1. Interested
2. Distressed
3. Excited
4. Strong
5. Irritable
6. Alert
7. Nervous
8. Determined
9. Attentive
10. Jittery

Additional to the previous questions, we will use adapted questions that are focused on this particular evaluation. For each of the three conditions, the participants will answer the following questions also on a Likert answer type scale from 1-7:

11. I found it difficult to carry out the Situational Awareness task
12. I had a sense of understanding my role.
13. How satisfied were you in your performance?

6. Post experiment questions

The following open questions will be asked at the end of the experiment to elicit open dialogue from participants

1. What difficulties did you encounter during the Situational Awareness task?
2. What elements in a display do you think would be necessary to perform SA?
3. Is there anything that you want to include about the experience that was not previously covered?

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[5] 8http://booksite.elsevier.com/9780123745170/Chapter%203/Chapter_3_Worksheet_3.1.pdf

7. Demographic Questions

To describe the participants who evaluate the system, the following demographic questions will be included.

1. Age
2. Profession/field of study
3. Gender (male, female or other)
4. Do you have experience with 3D computer games? (5-item scale)
5. How frequently do you play computer games?
6. Do you have experience with Virtual Reality Systems? i.e. HTC Vive HMD
7. Do you have experience with a simulator system? i.e. Flight sim/Driving sim
8. Are you involved in any activity related to fire-fighting / emergency situation intervention? (e.g. firefighter, first responder…)
    a. Please specify

8. Objective Performance Data

During the evaluation, we will collect the data on the performance of each user to carry out the Situational Awareness task. After all data have been collected the score based on the metrics supplied by the Subject Matter Experts will be calculated for each user and condition.

We will ask the participants to report what they see and hear during the experience. The more they report the higher score they will get in the self-reporting.

In addition we will assess be in the quality of the report, which is related to information of any significance to a fire risk, or risk to the operation and general the accuracy of the reported information.

Both metrics will be calculated based on the anonymized data collected once data collection of all the participants is completed.

A.3 Radio Communication Role-Play Scenario

The following content was used to generate and run simulated aerial firefighting scenarios. It is a component of the FENZ aircraft operations training. The content was used in both of the second and third user study.

US3293 Manage Ground Support For Aircraft Operations

Gold Creek Fire

A resource for Unit Standard 3293.
Ed 1. 11.05.

Gold Creek Fire Notes:

Kaweka State Forest Park (DOC East Coast – Hawkes Bay)

Fire Background.
A hunter lit a fire to boil his billy at the mouth of a steep sided north-facing gully in an unnamed tributary to the Ngaruroro River opposite Gold Creek on Wednesday the 10 th of October 1997. The hunter left the fire to get water from a nearby creek a few meters away but by the time he got back the fire had escaped. He tried to beat the flames out with his Swanndri and was helped by a passing helicopter pilot and passenger who saw what had happened. All three men failed to extinguish the fire and it escaped to burn over 75 ha at a cost of $260,000.

A family was staying at nearby Boyd Lodge (1030 m), 4 km to the North, noted the smoke about five minutes into the fire and video taped a large part of the subsequent days activities. Their video record is on the DVD.

The Fire Site.
The site is 70 km south east of Taupo airport (406 m) and 70 km north of Bridge Pa Airfield (20 m) near Hastings. There is no road access. <u>All access is by foot or aircraft</u>. The site is truly remote and at 1000 m altitude as depicted by the map overleaf. The fire ground is almost a classic “chimney”, facing north, covered in lighter fuels and merging to heavier hardwood Beech forest at the ridgelines. The fire ranged in altitude from 1020 to 1220 meters.

An airstrip (980 m) is formed to service Boyd Lodge guests and another airstrip (960 m) is near the mouth of the fire ground constructed by a private citizen for his own aircrafts use. This private airstrip is not portrayed on the topographic map but is clearly visible on the following images in Appendix 1.

Minor creeks and a major river with several deep water holes are close by the fire ground and can be seen on the following map.

Fire weather information is attached.

Points for Air Support Supervisors to Consider.
This is a really remote site 30 minutes flying from the nearest airport in a light aircraft. All resources (people, fire equipment, fuel and food) have to be flown in to the site before work can start. Because of the remoteness, special safety considerations need to be made for working in isolation, changes in weather, working at higher altitudes and differences in aircraft performance because of altitude or payload.

Once reported to the fire authority, the best they may know is that it’s a big fire, as they can see the smoke from Taupo, and that its somewhere near Boyd Lodge. They may not know any more than this. That you are provided with a map having many details should help you plan how you would do the job.

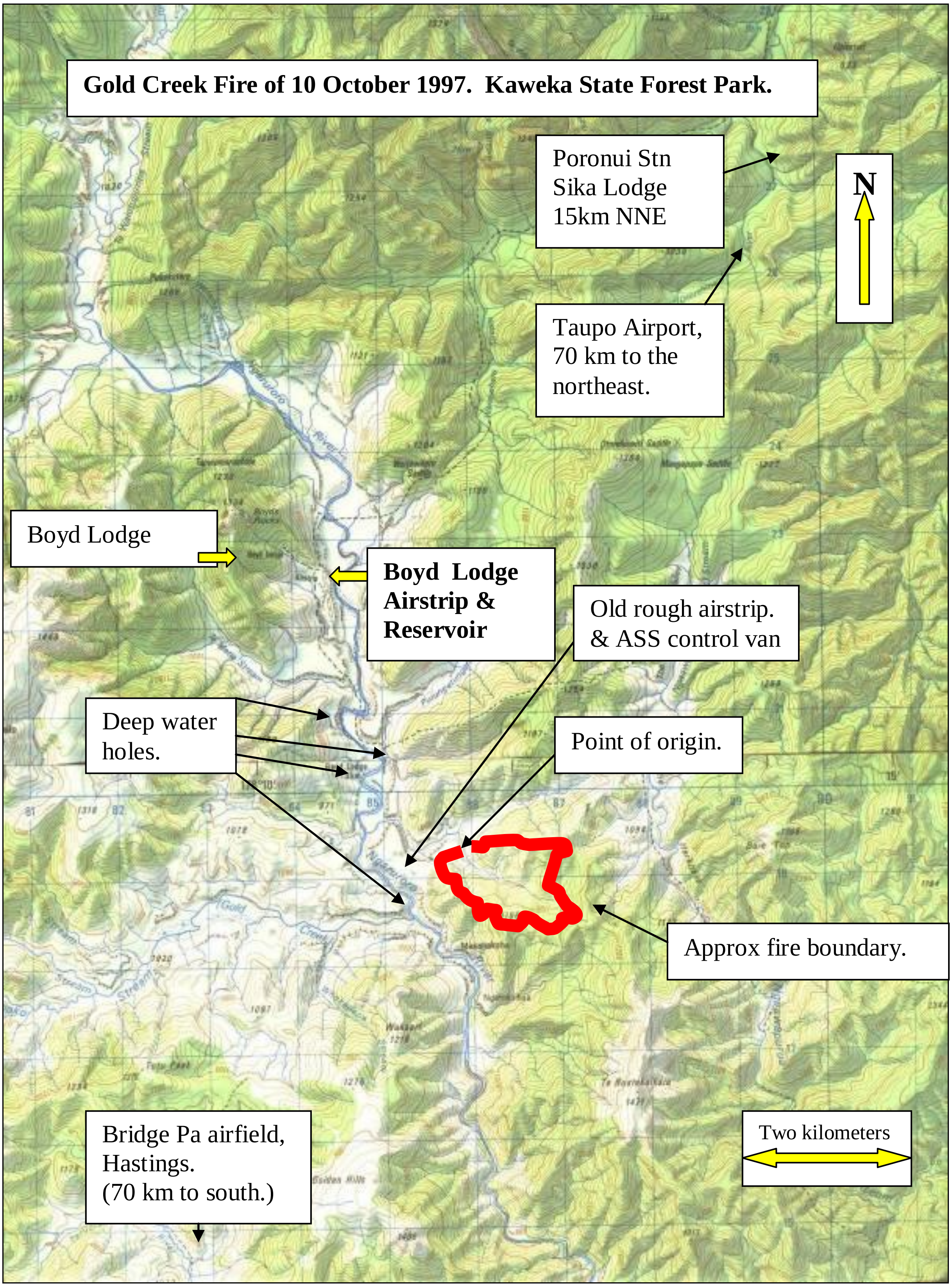
Gold Creek Fire of 10 October 1997. Kaweka State Forest Park.
Poronui Stn
Sika Lodge
15km NNE
N
Taupo Airport,
70 km to the
northeast.
Boyd Lodge
Boyd Lodge
Airstrip &
Reservoir
Old rough airstrip.
& ASS control van
Deep water
holes.
Point of origin.
Approx fire boundary.
Bridge Pa airfield,
Hastings.
(70 km to south.)
Two kilometers

Image 1. Approaching the fire ground from the west in a Cessna 172 on 29 December 1997, 19 days after the fire started. Dry tussock present and no roads at all.

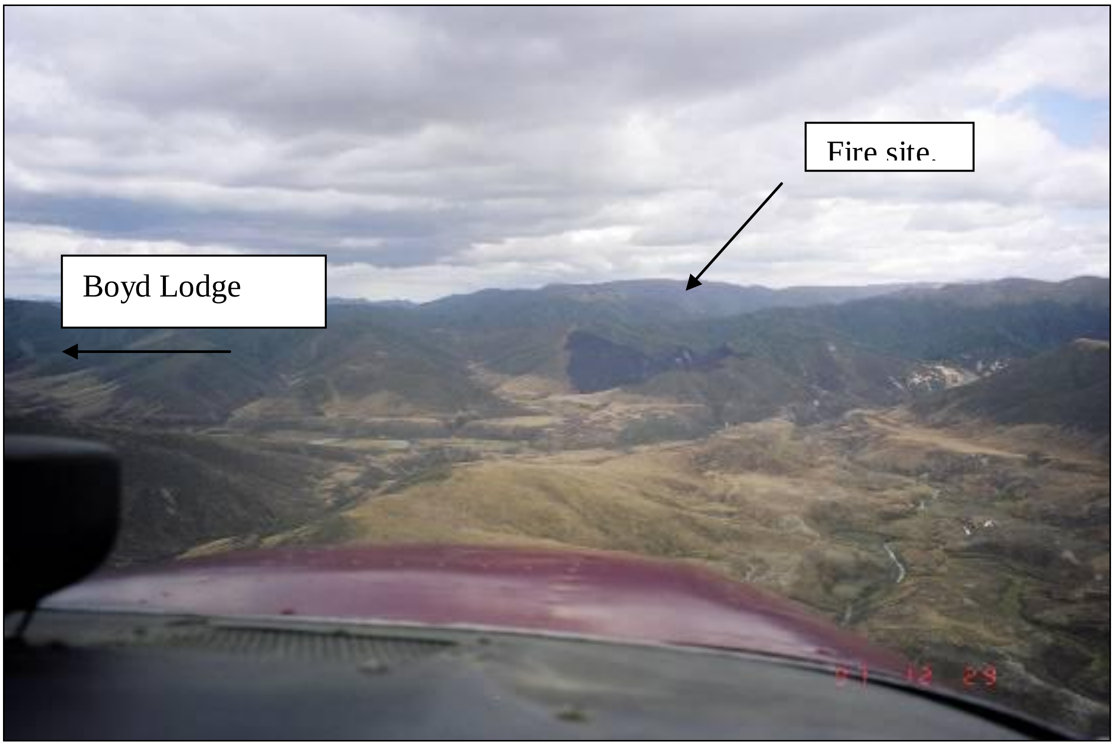

Image 2. Point of origin in the lower centre of the image. Rough airstrip to right. Note steep slopes, fine fuels and some heavy bush. (Rapid fire spread potential.)

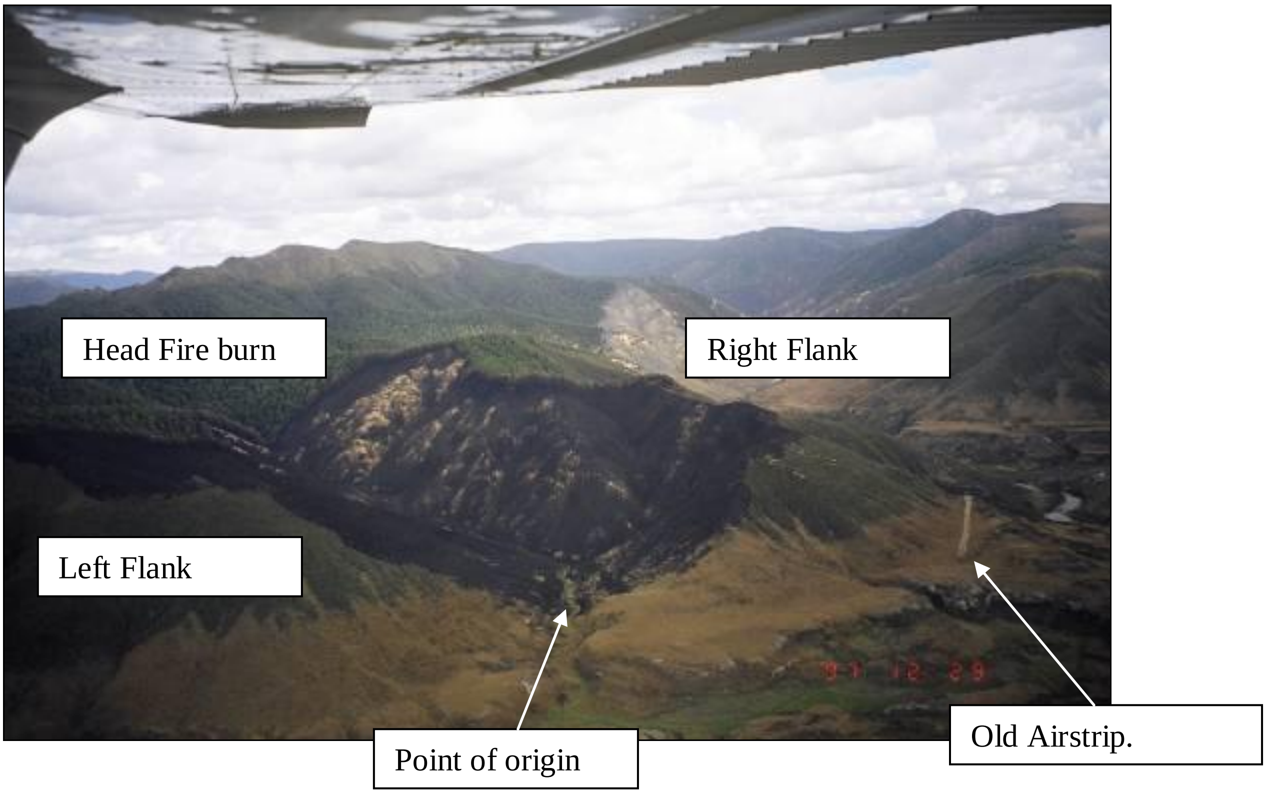

Image 3. Looking from the south, northwards to the Ngaruroro River, Boyd Lodge, 4 Km away and heavy burnt out bush. Large trees were felled on the fires ridges to stop ember transport.

Image 4. Looking generally east across the new and old burn sites. The fire did not stop at the ridge. Topography is steep with difficult aerial and foot access.

Gold Creek Air Support Supervisor Exercise

Red Syndicate Briefing:

1. Fire at Gold Creek (Map)

2. Escalating Situation

- WX Rising NW 15 -20 knots by 1400
- Temp 30 C by 1200
- RH 60% dropping to 29% by 1200
- Cloud 3/8 5000 cloud ceiling
- Rain Nil sig for 10 days

3. 12th December FWI Readings:

- FFMC 86
- DC 218
- Bui 53
- ISI 12.3
- FWI 26

4. Resources:

2 x 206 BJR's – 2 hrs fuel onboard, 2x 20 litre foam, On board foam C Dax

Pilots: Reg on HJR;
Bill on HDJ;

1 x 500D - 2 hrs fuel onboard. 1x 20 litre foam On Board C Dax;

Pilot: Huck on HUX

Bulk Fuel: 6 x 200 litre drums Jet A1 at Poronui Stn (Sika Lodge – 15km NE of fire with electric pump

Elements to Build into Your Plan/Actions:

- Comms Plan
- Logistics
- Fuel
- Additives
- Site selection etc
- Safety Welfare
- Allocation of tasks
- Communications Established
- Resource Logging
- Documentation
- Options analysis
- Logging of All Actions and Decisions
- Role Rotation During Exercise

Timeline: Red Syndicate

0600 Call from ops – what's the ETA for A/C ex Poronui at fire

Response ………

No response Prompt call from JR HJR Reg – "What's the tasking Ready to go ex Poronui – I will call 5nm inbound

ASS Update for Ops ETA for A/C

0630 Call from Huck –on site and fire is perking along up to the ridge and C-Dax is U/S.

0700 Call from Huck "We are not holding the fire - need more machines here please – it's about to hit the ridge".

0715 ***No response*** ….. Ops call .. Require 4 more helicopters

"Organising AAS ex Wairoa to lead Air Ops. ETA 11 am."

0930 Ops call …. Crew transport required ex Poronui. 8 ff (2 x 4 person crews with kits and hand tools)

1030 Sitrep Reg call HJR (Fire cranking wind gusting 15 knots on ridge marginal for us guys up here Bill call s HDJ Nah - I'm doing fine on the South flank.

Prompt Discuss options with Ops.

1045 Ops Call Looking for fire behaviour obs.

Reserve Injects:

A. Medivac twisted knee on left flank.

B. FF ex Taupo left medication in car at Taupo airport.

C. PRFO (Don Geddes) and Mayor want to go for overflight.

D. Biggest A/C goes U/S need engineer from Taupo Clogged filters. No machines in Taupo.

Gold Creek Air Support Supervisor Exercise

Blue Syndicate Briefing:

1. Fire at Gold Creek (Map - Photos)

2. Has Been an Escalating Situation

- WX Rising NW 10 – 15 Knots by 1600
- Temp 22 deg C by 1200
- RH 65% dropping to 40% by 1200
- Cloud 3/8 5000 cloud ceiling
- Rain Nil sig for 10 days

3. 12th December FWI Readings:

- FFMC 86
- DC 218
- Bui 45
- ISI 6.6
- FWI 12

4. Resources:

2 x 206 JR's – 2 hrs fuel onboard, 2x 20 litre foam, On board foam C Dax – enroute from Poronui Stn (Sika Lodge 15km NE)

Pilots: Reg on HJR;
Bill on HDJ;

1 x 500D - 2 hrs fuel onboard. 1x 20 litre foam on board C Dax;

Pilot: Huck on HUX – on site at old airstrip

Bulk Fuel: 6 x 200 litre drums Jet A1 at Poronui Stn (Sika Lodge – 15km NE of fire with electric pump

Elements to Build into Your Plan/Actions:

- Comms Plan
- Logistics
- Fuel
- Additives
- Site selection etc
- Safety Welfare
- Allocation of tasks
- Communications Established
- Resource Logging
- Documentation
- Options analysis
- Logging of All Actions and Decisions
- Role Rotation During Exercise

Timeline Blue Syndicate

0600 Call from ops – “what’s the eta for A/c ex Poranui Stn at fire”

Response ………

No response Prompt call from JR HJR Reg – “What’s the tasking inbound 5nm ex Poronui”.

ASS Update for ops ETA for A/C

0630 Call from Huck –on site and fire is perking along ridge and C-Dax is U/S.

0700 Ops call “We will have 8 X 4 person crews and gear at Napier airfield at 0900 for transport to Boyd strip Please arrange transport”

0715 Huck we are not holding the fire it’s about to hit the ridge need more machines here pleease.

0715 ***No response*** ….. Ops call .. Require 2 more helicopters 1,000L lift

0720 Organising an AAS from Wairoa to lead air ops. ETA 11:00

0730 Bill HDJ “Have you guys considered a TRA – an EC120 just flew past here real low.”

0830 Ops call …. Crew transport from Boyd to Fireground using R/W – “Is it available from fire AC ?”

0900 Sitrep Reg call HJR “Making good progress on lower flanks Really need some more guys on the ground to follow up”

0930 Bill – HDJ calls “I’m struggling on the South flank I need some ground crews up here **NOW…”**

Prompt Discuss options with Ops.

1000 Ops Call Looking for Sitrep.

Reserve injects:

A. Media request from Hawkes Bay Today and the Dominion

B. Radio call from EC120 HJAFA “TV3 Inbound for news shots will be landing interview youse fallas in 15 mins”

C. Al Morrison and Kate Wilkenson with Mayor want to go for over flight ***Now***. “Just look for the BMW on the Napier - Taupo Road turnoff”.

D. Cessna 206 has got a carb heat issue - returning to Napier.

Gold Creek Air Support Supervisor Exercise

Blue Syndicate Briefing:

1. Fire at Gold Creek (Map - Photos)

2. Has Been an Escalating Situation

- WX Rising NW 10 knots by 1500 – followed by a SW change at 15 knots.
- Temp 30 deg C by 1200 dropping to 18 deg after the wind change
- RH 45% dropping to 20% by 1200
- Cloud 5/8 5000 cloud ceiling
- Rain Nil sig for 10 days – No rain expected

3. 12th December FWI Readings:

- FFMC 97
- DC 450
- Bui 87
- ISI 12
- FWI 35

4. Resources:

1 x 500D - 2 hrs fuel onboard. 1x 20 litre foam on board C Dax;
Pilot: Huck on HUX – on site at old airstrip
Bulk Fuel: 3 x 200 litre drums Jet A1 at Poronui Stn (Sika Lodge – 15km NE of fire with electric pump

2 x Cresco XL Water bombers on Boyd Airstrip with 2 x 1400l minitanker fuel.
Pilots: Greg in PBK – 6 x 20 L foam
Phil in EEL – 8 x 20 L foam

Elements to Build into Your Plan/Actions:

- Comms Plan
- Logistics
- Fuel
- Additives
- Site selection etc
- Safety Welfare
- Allocation of tasks
- Communications Established
- Resource Logging
- Documentation
- Options analysis
- Logging of All Actions and Decisions
- Role Rotation During Exercise

Timeline Blue Syndicate

0600 Call from ops – "I need a recce over the fire – organise it and get back to me with a sitrep"

Response ....

No response Prompt call from Huck – "I am on the old airstrip – what have you got from me. I have my bucket with me but it is not rigged yet"

0630 Call from Huck – Overhead fire, left flank - fire is skunking along the flank below the ridge its not doing anything at present.

Looks like the right flank is starting to perk along above where the crews are working".

0700 Ops call "I need you to build a retardant line on the left flank from the base anchor point to the point on the ridge where the fireline breaks right toward the head"

"We have an expected wind change to the SW at 15 knots and I want to safeguard against a blow out on that flank"

"Let me know when you have the resources on site and have a plan – I want it built just below the ridge line on the north face – its about 1 km in length"

0715 Huck: What do you want me to do now – I think I could do some work with the crews on the right flank

0715 Ops call: Require 2 more helicopters 1,000L lift to work on the right flank – and get that 500 over ther to assess and then get him bucketing

Organising an AAS from Wairoa to lead air ops. ETA 13:30

0730 Huck "Have you guys considered a TRA – a local 185 just flew past here real low."

0830 Call from Greg in Cresco PBK – "Have you guys thought about using us on direct attack on the right flank until you are ready for the retardant line – we have enough fuel and foam and can work off the strip. It has a fire reservoir – we just need a fill crew"

Ops could get you a fill crew and a Waterous get onto him

0900 ***If no response*** – Ops call "I overheard the call from Greg – let's run with that but still keep the extra helos coming. I will get a fill crew on site asap"

Call from Huck "I have my bucket on and heading fro the right flank – Are you getting the fixed wings up here. Not sure about working in close with those guys. I might head to the left flank to get some airspace if you get those ships up here"

1000 Ops Call Looking for Sitrep. "Fill crew and Waterous on site – Boyd"

10:30 Call from Greg "Airborne with Phil in tow – where do you want us.

10:35 Call from Huck "Low on fuel will need to bug out now for fuel ex Poronui. I have the fixed wings in sight
"I will get onto the left flank when I get back and leave the right flank to Greg and Phil"

11:00 If no response: “Call from ops “ Get Huck back on the left flank when he gets back – tell him to follow in behind Phil and Greg to smudge out behind him”

11:30 Call from Greg “Making good progress – it will be good if we haqd the 500 following up our drops to smudge out”

12:00 Call from Ops – Sitrep required on fire and how is the planning for the retardant line build going – where is the Firetrol coming from”

Reserve injects:

1. Radio call from EC120 HJAFA “TV3 Inbound for news shots will be landing interview youse fallas in 15 mins”

2 Call from Phil in EEL – “I have a chip light on – returning to Boyd to check it out but I could be out of action until I get an engineer to look at it.”

Appendix B

Letters of Approval

B.1 Ethics

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

HUMAN ETHICS COMMITTEE

Secretary, Rebecca Robinson
Telephone: +64 03 369 4588, Extn 94588
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2017/21/LR-PS

18 August 2017

Rory Clifford
HITLAB NZ
UNIVERSITY OF CANTERBURY

Dear Rory

Thank you for submitting your low risk application to the Human Ethics Committee for the research proposal titled "Stress Management and skill training using Immersive Virtual Reality".

I am pleased to advise that this application has been reviewed and approved.

Please note that this approval is subject to the incorporation of the amendments you have provided in your email of 8th August 2017; **and the following:**

Please forward to the HEC a copy of the letter supporting your research from the Air Attack training organisers for our files.

With best wishes for your project.

Yours sincerely

pp. R. Robinson

Associate Professor Jane Maidment
Chair, Human Ethics Committee

UNIVERSITY OF CANTERBURY
Te Whare Wānanga o Waitaha
CHRISTCHURCH NEW ZEALAND

HUMAN ETHICS COMMITTEE

Secretary, Rebecca Robinson
Telephone: +64 03 369 4588, Extn 94588
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2017/56/LR-PS

27 October 2017

Rory M.S. Clifford
HIT Lab NZ
UNIVERSITY OF CANTERBURY

Dear Rory

Thank you for submitting your low risk application to the Human Ethics Committee for the research proposal titled "Exploring the Potential of Immersive Multi-Sensory Technology for the Purpose of Evaluation in Air Attack Supervision".

I am pleased to advise that this application has been reviewed and approved.

The Committee recommend that the data is stored on a University password-protected computer.

With best wishes for your project.

Yours sincerely

pp. R. Robinson

Associate Professor Jane Maidment
Chair, Human Ethics Committee

HUMAN ETHICS COMMITTEE

Secretary, Rebecca Robinson
Telephone: +64 03 369 4588, Extn 94588
Email: human-ethics@canterbury.ac.nz

Ref: HEC 2017/56/LR-PS Amendment 1

26 January 2018

Rory M.S. Clifford
HIT Lab NZ
UNIVERSITY OF CANTERBURY

Dear Rory

Thank you for your request for an amendment to your research proposal "Exploring the Potential of Immersive Multi-Sensory Technology for the Purpose of Evaluation in Air Attack Supervision" as outlined in your email dated 22nd January 2018.

I am pleased to advise that this request has been considered and approved by the Human Ethics Committee.

Yours sincerely

pp. R. Robinson

Professor Jane Maidment
Chair, Human Ethics Committee

B.2 Permission from FENZ

03/07/2018

To whom it may concern,

I, Richard McNamara, in my role as Regional Manager for FENZ, hereby give permission for Rory M.S. Clifford to publish my name and the details of my organisation in content pertaining to his thesis and research disseminations such as articles in conferences or journals.

Signed,

Richard McNamara

Region Manager Rural

Region 4

Fire and Emergency NZ